STANDARD POLYPHASE APPARATUS AND SYSTEMS

BY

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Mem. Am. Ins. E. E.

WITH 207 PHOTO-REPRODUCTIONS DIAGRAMS, AND 21 TABLES

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PREFACE TO FIRST EDITION.

THE development of polyphase apparatus and the application of polyphase systems to the solution of engineering problems, have been so rapid and varied of late, that there is no available literature on the subject which is at once practical and up-to-date. The excuse for this little book is the demand for information, in a convenient form, on the characteristics and uses of the various types of polyphase apparatus, and on the actual working of the several polyphase systems now sanctioned by the best practice.

These notes are intended for electrical engineers, central station men, and others who talk about, operate, or are interested in polyphase machinery.. While a certain general acquaintance with alternating-current apparatus is presupposed on the part of the reader, the author believes that the reader whose experience has been confined to direct-current machinery, will, nevertheless, experience no great difficulty in reading and understanding this book.

In view of the amazing increase in number and magnitude of installations for the transmission of power by polyphase currents, this book has been written with special reference to the problems that belong to this class of engineering work.

The author desires to acknowledge his indebtedness to many electrical manufacturing concerns for the use of much special and valuable information, and to the electrical press for the use of a number of plates.

NEW YORK, *June*, 1899.

PREFACE TO FIFTH EDITION.

THE printing of another edition of this little work has afforded the opportunity of bringing it up to date. While, since the appearance of the first edition, there has been a notable increase in the size of apparatus units and in the development of appliances for their control and protection, the practical workings of polyphase systems in the main have not changed. The same may be said of the commercial application of most polyphase apparatus, the details of construction of some types of which, however, have undergone considerable modification. The growing importance of the single-phase motor has been duly considered in the chapter on induction motors.

M. A. O.

SCHENECTADY, N.Y.,
July, 1907.

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STANDARD POLYPHASE APPARATUS AND SYSTEMS.

CHAPTER I.

INTRODUCTORY.

DEFINITIONS OF ALTERNATING-CURRENT TERMS.

Alternating Currents. — On account of the limitation imposed by the space of this book, mathematical demonstrations of alternating-current phenomena have been omitted in the following pages, and the chapter will be found to consist mainly of elementary explanations and statements which partake of the nature of definitions. It is hoped that these definitions will be found useful in aiding the uninformed reader to obtain a clearer understanding of the principles underlying polyphase apparatus and methods. For a more comprehensive treatment of alternating-current phenomena, the reader is referred to the many works on the subject.

The alternating-current generator was one of the earliest applications of the principles of induction. Unlike the current from the direct-current generator, which came at a later date, the alternating current rapidly changes its value and direction, the fluctuations being periodical. Such a current reaches a maximum in one sense, de-

clines to zero, reverses, and then attains a maximum in the other sense, as often as the pressure of the generator follows this variation.

Assuming, for simplicity's sake, the case of a two-pole alternating-current generator it can be shown that for various positions of the armature coil the number of lines of force enclosed is proportional to the cosine of the angle through which at any instant the coil has turned, starting from that position in which no electro-motive force (*E.M.F.*) is generated. The instantaneous value of *E.M.F.* generated at any position of the coil depends on the rate of change of the number of lines of force enclosed. The number of these lines being proportional to the cosine of the angle of rotation, this rate of change will be the same as the rate of change of the cosine, — that is, proportional to the sine, from which it follows that the instantaneous value of the generated *E.M.F.* is proportional to the sine of the angle of rotation.

The variation of induced *E.M.F.* being thus correctly representable by the sine function, we will draw the follow-

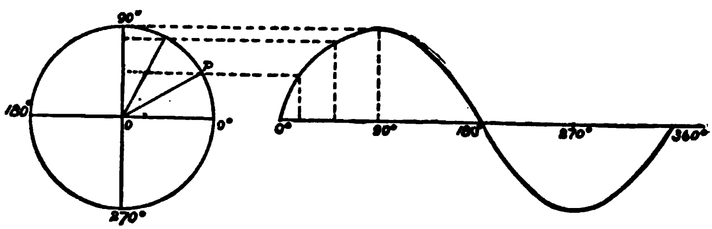


Fig. 1.

ing curve (Fig. 1) in which the horizontal distances represent angles of rotation and in which the vertical distances are proportional to the sine of these angles.

The circle at the left of the figure is drawn to show the method of developing the sine curve, the point *P* on the circle being considered as moving with a uniform velocity, and the projection on the diameter of the circle of the radius *OP* being at any instant proportional to the sine of the angle moved through. The vertical distances will also represent the various instantaneous values of the *E.M.F.* corresponding to the various angular positions of the coil, and the value at any instant is equal to the maximum value multiplied by the sine of the angle instantaneously occupied by the coil.

In the two-pole dynamo machine assumed, a single revolution of the moving coil has been seen to produce a positive sine wave of *E.M.F.* followed by a similar negative wave. At the end of the negative wave, and before another positive wave is started, the conditions are the same as at the beginning of the first revolution, and additional revolutions will produce only successive duplicates of the wave as drawn. The term "*cycle*" or "*period*" is therefore given to the complete series of *E.M.F.* changes as shown by the curve. The name "*frequency*" or "*periodicity*" is given to the number of cycles that take place in unit time of one second, and we speak of a frequency of 25 cycles per second, or simply say the frequency (or periodicity) is 25.

While the sine curve of *E.M.F.* is only approximately realized in the average alternating-current dynamo, the modern generator does not usually depart widely from it, and for general purposes no sensible error is involved in considering the *E.M.F.* wave as being sinusoidal.

On this basis, therefore, it remains to be seen what sort of reading will be recorded on a voltmeter at whose

terminals the *E.M.F.* is constantly varying according to the sine law. With any commercial frequency the variations of *E.M.F.* are obviously occurring far too rapidly to permit the voltmeter needle to follow them, and the needle will therefore take up some kind of average position. An alternating current will flow through the voltmeter, the alternating values of the current corresponding to those of the alternating *E.M.F.* Now, the heating effect or the dynamometer effect of any current (by which the value of the current is measured) varies as the square of its value. Hence where the current is not constant the heating effect or the dynamometer effect will be represented not by the average of the instantaneous values of the current but by the average of the squares of these values. This affords the means for determining that value of *E.M.F.* which if steadily applied will have the same heating effect or the same dynamometer effect (*i.e.*, which will give the same needle deflection) as that produced by the alternating *E.M.F.*; for what is now to be determined is only that value of steady *E.M.F.* (or current) whose square is the same as the average of the squares of the several instantaneous values of the alternating *E.M.F.* The shape of the sine curve is such that, given the maximum value, which we will call a, seen from Fig. 1 to be equal to OP the average of the squares of the instantaneous values can be shown to be equal to $a^2 \div 2$. The dynamometer effect being therefore $\frac{a^2}{2}$, the *E.M.F.* (or current) producing this effect is represented by the square root of this quantity or $\frac{a}{\sqrt{2}} = \frac{a}{1.414} = 0.707a$. This is the value which is indicated by all alternating current measuring instruments. It is

called the virtual or mean effective value, and by reason of the process by which it is derived is frequently written as $\sqrt{\text{mean}^2}$ and called the square root of the mean square, or, briefly, the root mean square. As seen, it is equal to 70.7 per cent of the maximum value. This means that when a voltmeter reads 70.7 volts the maximum peak of *E.M.F.* is 100 volts, or, on a circuit where the instrument reads 7070 volts, the maximum rises to 10,000 volts. In the case of a high tension cable working at 7070 volts (as read on a voltmeter) this means that twice in every cycle the insulation is subjected to a potential higher by 2930 volts than that indicated by the voltmeter, which registers only the effective *E.M.F.* or root mean square. The maximum is thus 41.4 per cent higher than the mean effective, and this is a point which must not be overlooked, since in the case of such a cable the thickness of the insulation must be proportioned not to the average or to the mean effective *E.M.F.* but to the maximum potential strain.

This feature is of all the more importance when consideration is given to the departures from the true sine form which are found to some extent in nearly all generators. Coincident with the wave form corresponding to the frequency are frequently found subsidiary waves known as *harmonics*. These are always odd number multiples of the fundamental frequency, that is, the frequency of the harmonics is always three, five, seven, etc. times that of the fundamental. In Fig. 2 is shown the effect of the third harmonic (triple frequency).

In Fig. 2 "1" is the fundamental, "2" is the triple frequency harmonic, and "3" is the resultant wave. That is, "3" would represent the actual wave shape of an alternator in which were present a triple harmonic of the mag-

nitude shown. Obviously in such a curve as "3" the ratio between maximum value and root mean square is greater than in a true sinusoid. Depending on the value of the harmonic relative to the fundamental, the distortion from the sine wave will be of greater or less importance.

The name *amplitude* is given to the maximum value of the wave. In Fig. 2 the amplitude of "1" is *a*; of "2" it is *b*, and the amplitude of the resultant wave "3" is *c*.

It is necessary to make use of some reference point in designating the epoch at which during the cycle some

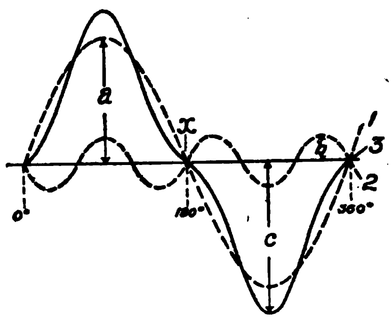


Fig. 2.

event occurs. This reference point is usually taken as that at which the positive wave makes its start. For curve "1" in Fig. 2 this is at o. It is also at o for curve "3." From *o* to *x*, where both these curves fall to zero again is 180 degrees, and *x* is said to be behind o by 180 degrees of *phase*. Similarly, the maximum of curve 1 is reached after 90 degrees of phase is passed through. If, as in Fig. 3, two waves are drawn as shown, wave *b* is said to be 90 degrees of phase behind wave *a* because *a* has advanced through 90 degrees of its course before *b*

starts out. Two waves having 90 degrees of phase displacement are often referred to as being in *quadrature*.

The formula for the flow of current in an alternating system of conductors is, in its general form, similar to that used for determining the flow in a direct-current system. It differs from Ohm's law only in the introduction of certain factors, which, however, may become so complex as to conceal the simple quantities of the equation for current, resistance and *E.M.F.* The value of these factors depends on three well-known properties of a conductor. These are:

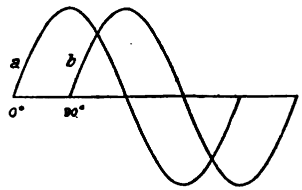


Fig. 8.

1. Inductance.
2. Capacity.
3. Virtual Resistance.

Inductance. — In the case of a direct current of constant value the magnetic field surrounding a circuit through which a current is flowing, exerts no influence on the circuit. In the case of an alternating current it is of great practical importance, and gives rise to a variety of phenomena. The magnetic flux then varies periodically with, and in the same manner as, the current and *E.M.F.* The setting up of this magnetic flux — or lines of force, as they are sometimes called — produces an *E.M.F.* in the circuit, in opposition to the induced *E.M.F.* This counter *E.M.F.*, or *E.M.F.* of self-induction, is strongest when the magnetic flux is changing most rapidly; therefore arriving at a maximum 90 degrees later than the flux and the current producing the flux. The result of this counter *E.M.F.* is that, when

an external *E.M.F.* is applied, the current does not immediately attain its maximum, and, when the *E.M.F.* is withdrawn, the current persists for a while. The current reaches its maximum later in point of time than the *E.M.F.*, — i.e., is always lagging behind the *E.M.F.* It would seem as if a current of electricity possessed a quality of the nature of the inertia of matter.

The strength of this flux, or the induction as Faraday called it, is determined by the current. The extent to which a gixen flux affects a circuit in a non-magnetic medium — i.e., the magnitude of the counter *E.M.F.* — depends solely upon the geometry of the circuit. If the circuit is wound in a coil, or so arranged that in the periodic variation of the flux the same lines of force encircle more than one portion of the conductor, the counter *E.M.F.* will be increased.

That constant quality of a circuit which determines its inductive effects is called inductance. The inductance may be either self or mutual inductance, according as the circuit is isolated or acted on by an adjacent circuit, also carrying a current. Inductance is frequently called the co-efficient of induction. The symbol L is used to designate self-inductance, — the unit of measurement of which is the henry.

Capacity. — Like inductance, the capacity of a circuit depends upon its geometry and its surroundings. It is the quality which a conductor possesses of being able to hold a quantity of electricity. A combination of conductors or conducting surfaces, advantageously placed to hold the greatest possible quantity of electricity, is called a condenser. All insulated lines act more or less like condensers. The charging or discharging current of a

condenser is greatest when the rate of change of effective pressure is greatest; that is, when the *E.M.F.* is at zero at the moment of passing from negative to positive, or *vice versa.* The effect of capacity, then, is opposite to the effect of inductance, and may neutralize it, or even overcome it, when existing in the same circuit. In a circuit having capacity, the current may lead the *E.M.F.* in phase. Fig. 4 shows the lead produced by capacity. The curve *V* represents the curve of *E.M.F.*, and *I* the current curve leading the *E.M.F.* The unit of measurement of capacity is the farad, and is usually represented by the symbol *K*.

Impressed E.M.F. — The more frequently an alternating current is reversed, the less time is there available for it to reach the value it would have in a direct-current system. To drive this maximum current through an alternating system of conductors having inductance, requires a greater *E.M.F.* than is needed in a direct-current system to produce this same current. The inductance of a circuit, as explained, determines the counter *E.M.F.*; and it must be overcome by an added amount to the *E.M.F.* required to produce the same current in a direct-current system. The name of impressed *E.M.F.* has been given to this resultant. The counter *E.M.F.* lags 90 degrees behind the current, and is greatest when the current is reversing its sign, or when the rate of change of the lines of force is greatest. The values and

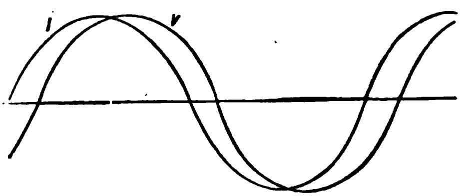


Fig. 4.

direction of the impressed *E.M.F.* and its components may be considered in a diagram. In Fig. 5 the impressed *E.M.F.* is shown as the hypotenuse of a right-angled triangle. That component of the *E.M.F.* which would drive the same current through a circuit without inductance, being necessarily in phase with the current, is shown as lagging behind the impressed *E.M.F.* by an angle, ϕ, and by a length equal to its magnitude. In quadrature with this component is the *E.M.F.* of self-induction, the magnitude of which determines the length of the line in the diagram. The magnitude of the impressed *E.M.F.* is then readily found. The name of energy *E.M.F.* has been given to that component in phase with the current, and which is effective in doing any work in a circuit. As all the quantities in the diagram must follow the law of simple harmonic motion, the curve of self-inductive *E.M.F.* will be shown in the same way as the curve of impressed *E.M.F.* The effect of this inductive component, in increasing the impressed volts needed to cause a given current to flow, is shown in Fig. 6. The curve RI represents the energy component of the impressed *E.M.F.* which would drive the current if there were no inductance. It is equal in value to the product of the current and the resistance. In quadrature with it, is the *E.M.F.* required to overcome self induction, designated by the curve pLI, p being equal to $2\pi N$, where N is the number of complete cycles per second, and L the inductance. This is the component required to offset the effect of the induc-

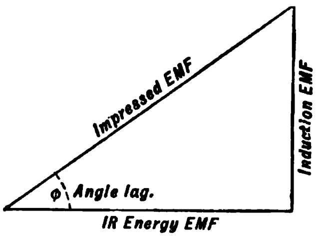


Fig. 5.

tance. By adding the ordinates of the two curves, we obtain a third curve, V, also following the sine-curve law.

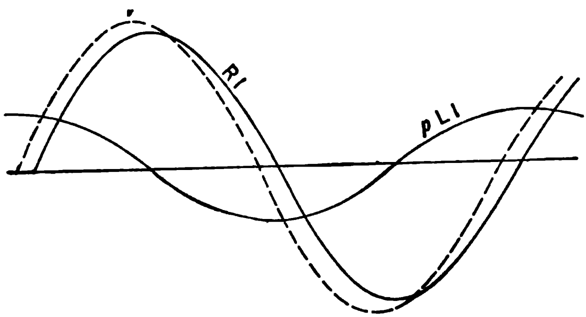


Fig. 6.

This is the curve of the impressed *E.M.F.* required to produce the given current in this particular circuit.

Impedance; Reactance. — Impedance is the total opposition in a circuit to the flow of current. It determines the maximum current that can flow with a given impressed *E.M.F.* It is made up of a resistance component and another component to which the name of reactance has been given. The relations of resistance, reactance, and impedance are shown in Fig. 7. As there may be energy losses external to a circuit, and yet dependent on that circuit, which require a flow of current that cannot be determined by a calculation based upon the ohmic resistance alone, it is not correct to designate the resistance com-

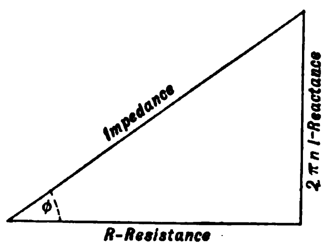


Fig. 7.

ponent as the ohmic resistance. Such losses are those due to hysteresis in transformers and iron cores. This component of impedance is termed energy resistance, and the other, reactance, which has sometimes been called the inductive resistance.

Reactance is the effect of self-induction expressed in ohms. It becomes prominent in lines of large cross section. The relative value of reactance to resistance can be reduced by selecting a number of conductors of small areas having a combined equal resistance. For instance, when for one No. 000 wire two No. 1 wires are substituted, the resistance will remain the same, but the reactance will be almost halved.

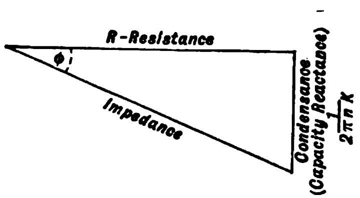


Fig. 8.

When capacity is introduced into the circuit, the current may lead in phase. Fig. 8 illustrates the effect of capacity on the circuit. The reactance due to capacity, or condensance as it is designated, acts in the opposite direction to the reactance of inductance. The impedance in Fig. 8 is the resultant of the resistance and the capacity reactance or condensance. When capacity and inductance are both present, the impedance is the resultant of the resistance component and a component equal to the difference between the numerical values of the condensance and reactance. In Fig. 9 the reactance is laid off above the line of resistance and in quadrature with it. The condensance acting in opposing direction is represented as having a greater numerical value. The resultant impedance is readily found. When the inductance is equal to the con-

densance, the current is in phase with the impressed *E.M.F.* and follows Ohm's law.

In aërial conductors of low resistance, the reactance is often prominent, and the distribution of *E.M.F.* may be seriously affected by it. It becomes important, then, in selecting conductors for transmission lines, that those of large cross-section, and correspondingly low resistance, be avoided as much as possible, except in special cases, as, for instance, in a rotary converter supplied by its own set of conductors, where some reactance may be desirable.

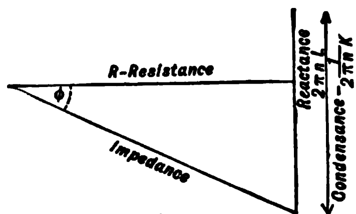


Fig. 9.

Virtual Resistance. — If the cross section of a conductor carrying an alternating current is resolved into many elements, it will be seen that the internal portions are subject to greater inductive effects than the elements nearer the surface. The outer streams of current suffer less opposition, and reach a maximum sooner than those centrally located. In large conductors, carrying heavy currents of very high frequency, there may not only be no current flowing in the central portion of the conductor, but a condition may exist where a current will flow in the opposite direction. The central core is then not only valueless as a conductor, but had better be omitted.

As a result of the reduction of the effective cross section of a conductor carrying an alternating current, the resistance is increased, and slightly less current will flow than would if the specific resistance and the inductance of the wire are alone considered. This increment of resistance

of a conductor is called its virtual resistance. The phenomenon is also called the skin effect.

The best shape for conductors of large cross section, carrying heavy alternating currents, is that of a tube or flat strip.

In common practice the sizes of wire and the rapidity of current reversals are not such as appreciably to produce this effect. The ratio of the resistance of a conductor carrying an alternating current, to its resistance when a direct current is flowing, can be readily computed for different sizes of conductors and reversals of current.

In Fig. 10 the ordinates represent the product of area and cycles per second. Corresponding factors for the virtual or apparent resistance of cylindrical copper conductors are read off the horizontal scale. The ordinate for the factor for a conductor of any other non-magnetic metal is the product of the ratio of its conductivity to that of copper, and the sectional area times the frequency. In the case of magnetic materials, especially iron, the factor for the virtual resistance is greater than that in the curve.

Energy in a Circuit. — The work done in a circuit will always be some product of the current and the quantities in phase with it. In a direct-current system the product of measured volts and amperes will give the energy of the circuit. In an alternating-current system the product of the measured amperes, and the component of impressed *E.M.F.* in phase with the current, — i.e., the energy *E.M.F.*, — will give the energy. The component of *E.M.F.* in quadrature with the current — i.e., the inductive component — drives a wattless current, and consequently adds nothing to the energy of the circuit. The product of the impressed *E.M.F.* and the current gives only the apparent watts of the circuit. The error in calculating

the power by the product of measured amperes and volts will depend upon the extent of the displacement in phase of the impressed *E.M.F.*, and the current, or the angle of the lag or lead, usually denoted as ϕ. The energy in the

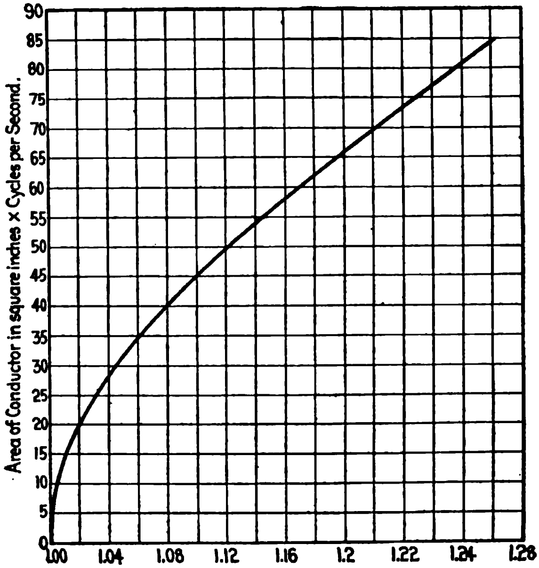


Fig. 10.

circuit can be found by multiplying the product of volts and amperes by the cosine of this angle.

Power Factor — Induction Factor. — The ratio of the true watts in the circuit, as measured by an indicating wattmeter, to the apparent watts, — the volt-amperes,— is called the power factor. The value of power factor is useful in determining the true energy in a circuit when the apparent

energy is known, the resistance when the impedance is known, the energy volts when the total impressed volts are given, and the energy current when the total current is known.

The quantities in quadrature with the energy values of current and *E.M.F.*, and with the resistance, may be determined in the same way, from the resultants by a multiplier or factor, called the induction factor. As the power factor is proportional to the energy components, and the induction factor to the components in quadrature with them, it follows that the former must be numerically equal to the cosine, and the latter to the sine of the angle of phase displacement. Accordingly, a table of cosines and sines for all angles will give the corresponding power and induction factors.

Wattless Current. — The component of the total current in quadrature with the energy current is called the wattless current. It should be understood that the current and other quantities of a circuit are resolved into components only for the sake of a better understanding of the phenomena taking place in the circuit. There is actually but one current flowing, as there is but one *E.M.F.*, in any one part of a circuit. The presence of reactance, either in the transmission circuit or in the apparatus connected to it, increases the lag-angle, and consequently the wattless current. This component does no work in a circuit, but increases the total current, and thereby the heating of conductors. The wattless current required to balance the reactance may become sufficiently great to practically tax the full capacity of generators and of conductors, although very little energy is being generated or transmitted. If it were possible to have conductors without resistance, a true wattless current could then, in fact, actually exist in

an alternating-current circuit. In such a case the total current would be in quadrature with the impressed *E.M.F.*, and the circuit would give back as much energy as it received, the sum being zero.

Relative Values. — Designating the current as I, resistance as R, reactance as S, and impedance as U, from what has preceded, the following relations will be understood:

1. The reactance of a line, S, $= \dfrac{\text{Induction } E.M.F. \text{ consumed in line}}{I}$.
2. The impedance, U, $= \dfrac{\text{Impressed } E.M.F. \text{ consumed in line}}{I}$.
3. The energy component of *E.M.F.* consumed by the resistance, R, of a conductor is IR, and is in phase with the current.
4. The inductive component of *E.M.F.* consumed by the reactance, S, of a conductor is IS, and is in quadrature with the current.
5. The impressed *E.M.F.* consumed by the impedance, U, of a conductor, is IU.
5. The energy loss in a conductor is I^2R, and depends on the current and resistance only.

Voltage Drop Dependent on Load Characteristic. — The *E.M.F.* consumed by the impedance, IU, does not represent the voltage drop in a conductor, as it is usually out of phase with the impressed *E.M.F.* as well as with the current. This voltage drop, as will be shown, can be anything between IR and IU. It will depend upon the difference in phase between the current and the impressed *E.M.F.*, or the lag angle, and can be determined when the power factor is known. In Figs. 11 to 16, let OE' be the *E.M.F.* at the receiving end of a transmission line. For various

power factors at the receiving end of the line, there will be corresponding phase differences, ϕ. Let OI be the current out of phase with the $E.M.F.$ by ϕ. IU, IR, and IS have the relations heretofore assigned to them, IR being in phase with OI, and IS in quadrature with OI. Where these quantities are small relatively to the impressed $E.M.F.$, as they usually are in practice, the drop of voltage is IA, equal to $OE - OE'$, OE being equal to the generator voltage, A the apparent resistance of the line.

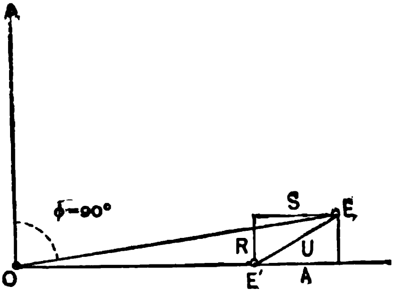


Fig. 11.

Assume a given $E.M.F.$ at the end of the line, and a constant resistance and reactance. If the phase displacement ϕ, or what is the same, if the power factor of the receiving system, is varied, the triangle of electromotive forces will revolve around E' as a center. The projection of IU, or its components, upon the $E.M.F.$ will give the voltage drop. With a lag angle of 90° (Fig. 11), the drop of voltage is due to the reactance alone. As the lag angle decreases, the drop IA becomes less than the impressed $E.M.F.$ consumed in the line IU until it reaches 60° (Fig. 12), when with the given values of IU and IS the drop is seen to be equal to the

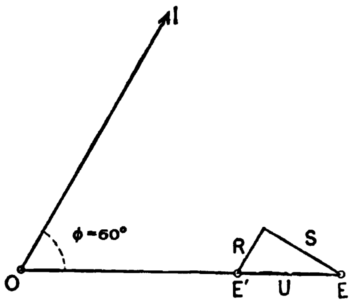


Fig. 12.

impedance IU, and has the greatest value it can have. As the phase displacement grows less, the effect of the reactance decreases until $\phi = 0$ (Fig. 13), when the drop is due to resistance alone, a case of a non-inductive load.

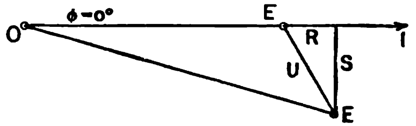


Fig. 13.

If capacity effect is now introduced into the line by the use of long cables, over excited synchronous, motors, over excited rotary converters, or of condensers, the phase displacement ϕ becomes negative. Up to 30 degrees the projection of the reactance is in opposition to the projection of the impedance, *i.e.*, negative (Fig. 14), and as a result the drop IA is less than the resistance drop. Finally, at 30 degrees (Fig. 15) there is no drop of voltage in the line; for the reactance raises the voltage as much as the resistance lowers it, and the line apparently has no resistance. As the phase displacement increases, the voltage at the receiving end becomes higher than the generator *E.M.F.*, due to the predominating effect of the condensance over the resistance. This is the greatest at 90 degrees (Fig. 16). For the sake of simplicity we have assumed in the foregoing that the projection of E deter-

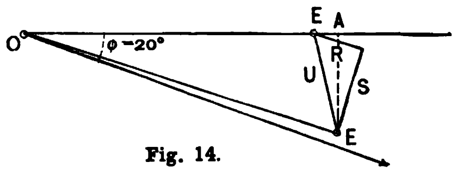


Fig. 14.

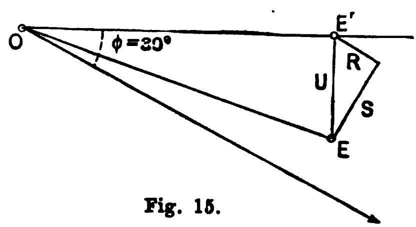


Fig. 15.

mines the apparent resistance. This is not strictly accurate, but in practice the error involved will be found to be insignificant.

Frequency. — As previously stated, the term cycle or period is given to the complete series of *E.M.F.* changes as shown by the curve in Fig. 1, and the name frequency or periodicity is given to the number of cycles that take place in one second. The same nomenclature is used with any other alternating quantities, such as current, flux, etc.

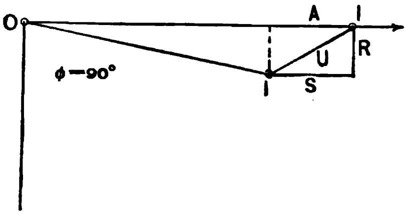


Fig. 16.

In a bipolar generator every revolution of the armature corresponds to one cycle. In multipolar generators there will be as many cycles for every revolution as there are pairs of poles. In a twenty-four pole generator of 300 *R.P.M.* there will therefore be five revolutions per second and twelve cycles per revolution, equalling sixty cycles per second. Frequency is sometimes stated in alternations per minute. As there are two alternations to each cycle the number of alternations per minute will be $2 \times 60 = 120$ times the number of cycles per second, and the generator in question would give $60 \times 120 = 7200$ alternations.

From the above we have: —

a) Frequency in cycles per second $= \dfrac{\text{Poles} \times R.P.M.}{2 \times 60}$

b) Frequency in alternations per minute $= \text{Poles} \times R.P.M.$

CHAPTER II.

GENERATORS.

As an elementary form of polyphase generator we may take the case of two single-phase alternators coupled together on one shaft in such a manner that the electromotive forces at the terminals of the respective armatures arrive at a maximum 90 degrees, or one-quarter of a period, apart. The currents from such a machine are said to have a two-phase relationship. An arrangement of three such armatures with similar coils one-third of a pole arc, or 120 electrical degrees, apart, will generate three-phase currents. Fig. 17 illustrates the armature connec-

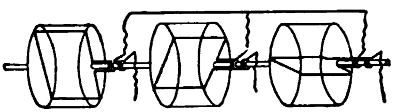


Fig. 17.

tions of such a three-phase unit made up of three single-phase alternators arranged in the manner indicated.

The combination of two or more independent alternators forming one polyphase unit facilitates the regulation of the circuits in case of unbalancing since the fields (not shown in the diagram) in which the respective armatures revolve, are separate and may be individually adjusted. Such a form of polyphase generator is not commercially

manufactured as it is naturally expensive. Being made of smaller machines, the cost is greater than that of a single unit of the same output. In a machine for the generation of polyphase currents, therefore, the several windings for the different phases are wound upon the same armature, the coils being angularly displaced to obtain the necessary phase relation. Since the flux which generates the voltage in the several phases is not a maximum in each phase at the same instant, the total quantity of armature iron may be considered as usefully employed by each phase successively. In this way the same quantity of iron is more economically employed in a polyphase than in a single-phase armature. As a result, polyphase generators are smaller and cheaper than single-phase generators of the same capacity. With the type of construction commonly employed, therefore, the polyphase generator has but one field and one armature, with as many sets of windings as there are phases. Irregularities in the voltage of the different phases, if any exist, must be overcome in some other manner than by the variation of the field strength. In some inductor types of generators this regulation is obtained by varying the number of armature turns in the unbalanced phase.

In general, the principles of construction and operation of single-phase generators apply equally well to polyphase machines.

Revolving Armature Type. — A type of alternating current generator at one time commonly employed is that in which the armature is the moving member. A typical machine of this class of 400 kilowatts capacity, is well illustrated in Fig. 18. This type resulted naturally from the accepted and necessary form of construction used in

direct current machines in which the armature is made the revolving member because otherwise the current collecting

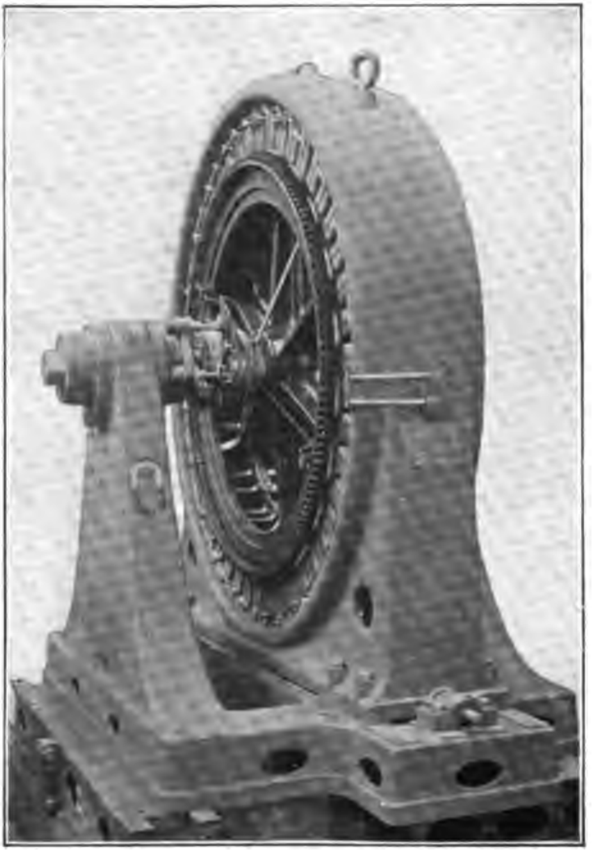


Fig. 18.

brushes would have to revolve also, an arrangement involving difficult and almost prohibitive operating conditions.

Revolving Field Type. — So far as concerns, however, the generation of *E.M.F.*, all that is required is relative motion between armature and field, and the same effect is produced by keeping the armature stationary and revolving the field as results from the reverse operation.

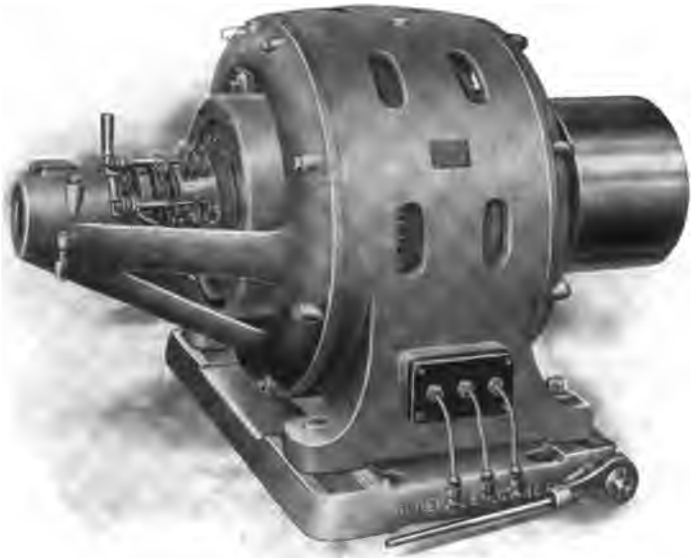


Fig. 19.

In the construction of alternating current generators it has in general been found more desirable to make the armature the stationary member, and most alternators are now built in this type. The advantages are principally the avoidance of moving contacts except such as are required for the moderate and low potential currents required for excitation. The stationary armature machine

is also more readily adapted to the generation of currents at high potential as it is easier to insulate and support the armature coils securely where they are stationary than where they are subjected to the centrifugal and vibrational strains which they would otherwise have to withstand.

Fig. 20.

The revolving field type of generator shown in Figs. 19, 20 and 21 is one of the number of forms of the stationary armature machine. The generator illustrated is of 100 kilowatt capacity at 2300 volts. It has eight poles, runs at 900 revolutions per minute, and consequently delivers current at a frequency of 60 cycles.

Fig. 21 shows the revolving field of this generator. It consists of a heavy cast steel center, to which are keyed the pole pieces projecting radially outward. These are built up of laminated sheet iron in order to minimize eddy current losses. The coils are wound on spools placed on the poles and held in place by the pole tips. In the illustration, metal pieces, or bridges, are shown between the pole tips. Bridges of this or equivalent form are sometimes desirable to facilitate parallel operation of generators. Bridges are also sometimes used on synchronous motors

Fig. 21.

to prevent the pulsation which is likely to occur under unfavorable conditions.

The field coils are preferably made of a single spiral of strip copper, wound on edge, as illustrated in Fig. 22, (which shows the construction of the field spools of a 750 kilowatt generator), the field poles being in this case secured by bolts to the periphery of the field ring. Mechanical difficulties in forming this edgewise winding prevent the use of very thin strip, and as a result the total resistance of a strip winding of this kind may be so low in a generator of small capacity having few poles that a low

voltage for excitation is desirable in order to prevent excessive waste of energy in the field rheostat. While a potential of about 125 volts is commonly in use for the excitation of alternators, it may, under the conditions described, be advisable to excite from a circuit of lower potential, as, say, 60 volts. When, as shown in the illustration, the alternator is equipped with its own exciter, the voltage of the exciter may be chosen at any value which is desired, and for very small machines such ex-

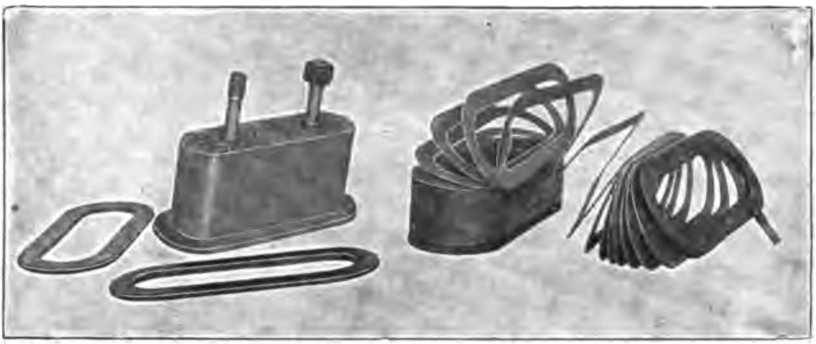


Fig. 22.

citers are frequently wound for 60 volts. Current from the exciters is often used for other purposes than for excitation, as for station lighting, and in such cases it is desirable to adhere to about 125 volts. In such cases small alternators with few poles have the field coils wound of wire so as to make the size of the field conductor appropriate to the excitation voltage. The strip winding is, however, simplest and best, as it is more easily insulated and dissipates the heat more readily. Direct current for

excitation is carried to the field windings by means of two cast iron or copper collector rings equipped with carbon brushes, requiring practically no attention in operation.

The stationary armature shown in Fig. 20 is of the iron-clad type and is built up of laminations slotted to admit the coils.

Fig. 23.

These are usually machine-wound and held firmly in place by wedges of seasoned wood. Any injury to the insulation from lightning or other causes is usually limited to one or to a few adjacent coils, which can easily be replaced without disturbing the rest of the winding.

Fig. 23 shows a typical Westinghouse belted alternator of 200 kilowatt capacity. It has 24 poles and runs at 300 revolutions per minute, giving 60 cycles.

All of the standard belted polyphase generators of the revolving field type conform to the general lines of the generators shown in Figs. 19 and 23. Generators of an output greater than 200 kilowatts are usually provided with a third, or outboard, bearing, to sustain the weight of the pulley and strain of the belt. Generators of 500 kilowatts and over are almost invariably built for direct connection to either engine or water wheel. If built for connection to the former the base is ordinarily omitted, while generators for coupling to water wheels are commonly provided with base and two bearings, and in small sizes are self-contained as a rule, the base and two bearings either comprising one casting or consisting of two bearing standards dowelled and bolted to the cast iron base, or following the construction shown in Fig. 19, having the bearings supported by the end shields, a construction which saves in floor space, weight and cost. Whenever possible, a generator, irrespective of its size, should be direct connected on account of saving of space and of belt losses, providing the increase in cost incident to slower speeds, if such are necessary, does not offset the advantages mentioned.

Fig. 24 shows the construction of the stationary armature of the machine of which the field coils are shown in Fig. 22. The revolving field acts like a fan, forcing the air outwardly through the openings, or air ducts, between the armature laminations.

The stationary armature consists of a circular cast iron frame, or spider, inside of which are dovetailed sheet steel

discs, with slots to receive the coils. Ventilating spaces, or ducts, are left between the laminations, through which the air flows rapidly when the generator is running.

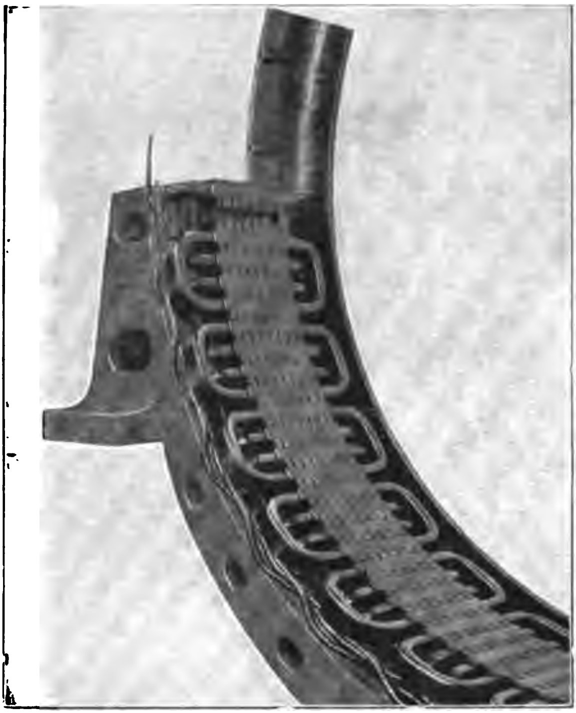


Fig. 24.

Fig. 25 is a sectional view of the field and armature of a typical revolving field three-phase generator. The relation of the magnetic circuit to the armature coils is clearly shown.

The generator shown in Fig. 26 is one which has recently been put in service at the station of a water power company in Mexico, and is a good example of a modern, high speed, three-phase alternator of large capacity. It has 14 poles and runs at 514 revolutions per minute, giving a frequency of 60 cycles. The driving power is supplied by a high head turbine direct coupled to the shaft, the half

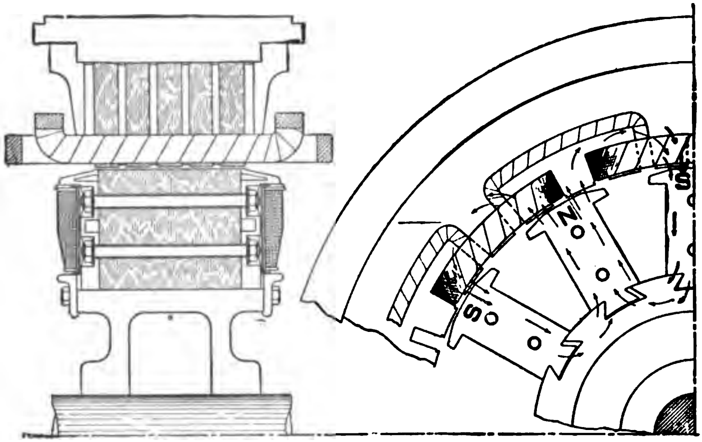


Fig. 25.

coupling on the generator end being forged integral with the shaft. The machine is wound for 2300 volts and delivers 752 amperes in each phase when generating its normal output of 3000 kilowatts. The commercial efficiency of this machine at full load is 97.3 per cent. The regulation at non-inductive load is 5.5 per cent. The revolving field is mounted nearer to one than to the other bearing so that when the armature is slid along the

Fig. 26.

machined surface of the base toward the observer, the windings are made accessible for inspection or repair.

Another form of the stationary armature type of generator is one in which the field winding is a single coil. The exciting coil is wound on a bobbin occupying a channel on the periphery of a cast-iron wheel. Two steel rims are bolted to this, the laminations being formed into poles. This is one of the original forms of polyphase generator; and this construction, which has considerable merit, was adopted in the early days of power transmission apparatus by European manufacturers.

Inductor Type. — Another modification of the stationary armature type is the inductor machine, manufactured to some extent abroad, and in this country chiefly by the Stanley Electric Company and by the Warren Electric Manufacturing Company. The distinguishing characteristic of this type is that any one set of armature coils, or portion of the armature conductors, is subjected to a magnetic flux of one polarity only. The magnetism fluctuates from zero to maximum and back again and does not reverse its sign. Most generators of this type have both fixed armature and fixed field windings, the only moving part being the inductor — a laminated iron core with polar projections. The exciting winding, wound into an annular coil, is sometimes placed centrally on the internal surface of the armature spider, embracing the revolving element, as in the Stanley machine. This is usually a ring of iron with a double row of laminated polar projections. In some machines, such as those manufactured by the Warren Company, the armature has a single set of coils, and the inductor is provided with a single row of laminations. The annular exciting coil may be part of the revolving element, and revolve with it.

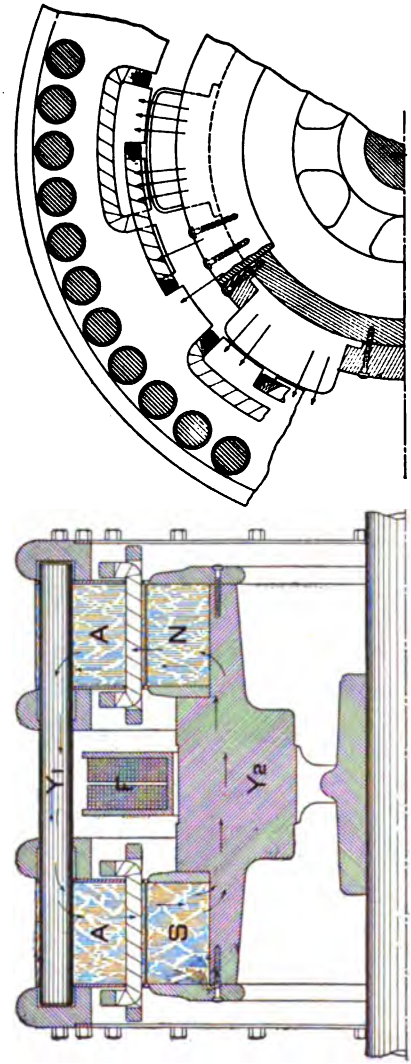


Fig. 27.

Reference to Fig. 27 will show the general arrangement of the magnetic circuit of the Stanley inductor generator. The annular field coil, *F*, is surrounded by the magnetic circuit, made up of the laminated cores *AA*, the armature yoke Y_1, and the laminated poles *N* and *S*, and the field yoke Y_2. The armature windings, consisting of two com-

Fig. 28.

plete sets, are laid in grooves in the armature cores in a manner similar to the revolving field-machine. It will be seen that the north and south poles do not alternate, but the magnetic flux simply pulsates in one direction. Only one-half of each turn of the armature winding is in an active field at one time, the other half of the coil being between the poles in an inactive field. The *E.M.F.* gen-

erated is one-half as great as it would be if the polarity of the flux were reversed. In order to obtain a given *E.M.F.* with the inductor type of machine, either the armature windings or the total magnetic flux must be doubled. The essential characteristics, therefore, of an inductor generator are a rather high density of the magnetic circuit, and a short air gap, the latter in order to reduce the magnetic leakage to a minimum. The stationary element of the Stanley inductor machine consists of two series windings,

Fig. 29.

forming two separate armatures. The currents in the coils are usually in quadrature with each other, thus giving a two-phase current. A three-phase relationship can be established by means of a symmetrical three-phase winding, or by making one set of coils with 0.86 the number of turns of the other, and connecting the end to the middle of the larger coil. By the theory of the resultant of electromotive forces, the currents in the three circuits will be equal, and the impulses will follow one another at intervals of 120 degrees. Fig. 28 shows a typical Stanley

inductor generator in course of assembly. Fig. 29 shows a portion of a similar machine in which the details of the armature and field construction are seen.

Fig. 30 shows a sectional view along the shaft of an inductor generator manufactured by the Warren Electric

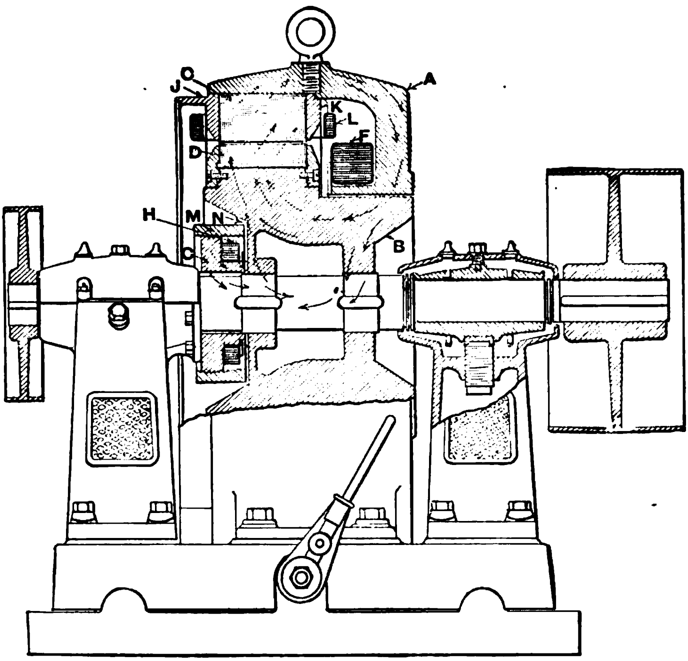


Fig. 30.

Manufacturing Company. *A* is the frame, or spider, of the stationary armature, into which are dovetailed the armature laminations *C*. *L* are the armature coils embedded in the iron. The revolving element is made up of the spider *B* carrying the laminated polar projections *D*. *F* is a single magnetizing coil. The

magnetic circuit is from *B*, through *D* to *C*, and thence from *A* to *B*. It will be seen that there are two air gaps, one between *D* and *C*, and the other between *A* and *B*. *H* is an auxiliary magnetizing coil, the purpose of which is to counterbalance the magnetic pull due to the main field coil *F*, so that there shall be no unbalanced pull in one direction or the other along the shaft. As in all inductor generators, the magnetism pulsates only, and the revolving polar projections have one polarity.

Generators with stationary armatures are now wound for pressures up to 18,000 volts, and there are no insuperable difficulties to be encountered in winding them for even higher potentials. The tendency, however, is toward the use on transmission lines of potentials higher than machines can well be designed to generate directly, and as transmission potentials of 60,000 and 80,000 volts and higher have either already demonstrated their commercial success or are to be attempted in the near future, it is probable that in order to reduce the cost of the line the higher potentials will in all cases be employed. As these potentials are probably beyond the limit of voltage that can be economically generated direct the use of set-up transformers for these extra high potentials will continue, and generators of 18,000 volts and over will be the exception.

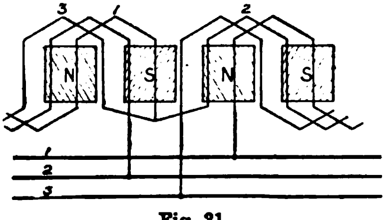


Fig. 31.

Armature Windings.—For details of windings of generator armatures the reader is referred to the comprehensive works on the subject. The armature windings of polyphase

generators are composed of two or more groups of single-phase windings suitably connected to give the desired phase relation. Fig. 31 shows the elements of a typical three-phase winding. The armature windings of the modern alternators are laid in slots or grooves below the surface of the armature punchings. The shape and number of the slots have a material effect upon the performance of the generator. The old-fashioned iron-clad armature had one coil for each pair of poles, laid in deep slots. On account of this grouping of the conductors into a coil of many turns, this generator possessed high armature reaction

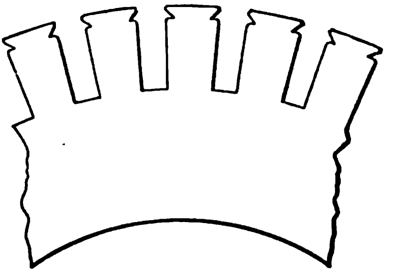


Fig. 32.

and consequently poor regulation, and could be short-circuited with no bad effects. This construction is sometimes carried out in those modern polyphase generators whose armatures have one slot for each phase and each pole, and are called unitooth machines. Thus the armature of an eight-pole, two-phase generator would have eight coils and a three-phase generator of the same number of poles would have twelve coils. The shape of the armature punchings of a twelve-pole, unitooth, three-phase, revolving armature generator is shown in Fig. 32. Sometimes the laminations have circular holes instead of slots. In this case the armature conductors are threaded through these holes by hand. As the surface of the armature (the holes being beneath the surface) is thus continuous, there is little or no tendency for eddy currents to

be set up in the faces of the field poles, which can therefore be cast solid, instead of being laminated. This is considered an advantage by some makers, the cost of the field poles being thereby reduced and a certain useful effect, equivalent to that secured by bridges between the pole tips, being secured. With this form of armature construction, however, the difficulty of repair is enhanced, as the coils are not readily removable, as in the case of open-slot machines. Armature reaction deforming the wave shape of the *E.M.F.*, and high self induction, requiring large exciting currents at full load, are often characteristic of the unitooth winding. Such generators can, however, be designed so as in a great measure to overcome these objections. It is fortunate that this is so because certain generators of high potential are more readily constructed in the unitooth design by reason of the greater economy of insulating space secured.

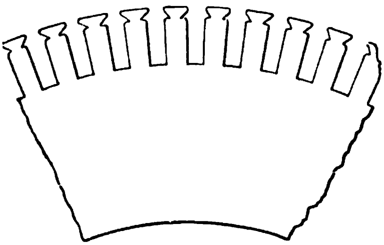


Fig 33.

Most modern polyphase armatures have two or more slots per pole per phase. The slots are open, which, with the distributed form of winding, gives a very low inductance. Fig. 33 shows the armature punchings of such a machine. The low inductance, together with lessened armature reaction which this construction insures, improves the regulation of the machine, in other words, reduces the increase of exciting current at full load. Generators with multitooth armatures are in general more

suitable for long-distance transmission at high potential. Their regulation is good and the wave shape approaches a sine curve, the best shape for this work, as it reduces the possibility of resonance, or rise of voltage at a distant point in the transmission circuit above that at the generator end.

The various connections of generator armature windings will be found explained in the chapters on polyphase systems.

Electromotive Force. — The drop in *E.M.F.* at the terminals of a direct current generator, as the output is increased, is due principally to the armature resistance and armature reaction. In alternators the resistance drop (*I.R.*) is generally not so prominent as that due to inductance and to armature reaction. The counter *E.M.F.* of self-induction lowers the terminal pressure on the usual loads with lagging component, while armature reaction, by opposing its flux to the field magnetism, reduces the effective number of lines of force passing through the armature conductors with the like result.

The inductance of unitooth armatures can be lessened by widening the opening of the slots, which, at the same time, increases the resistance to the magnetic flux, i.e., the reluctance of the air gap. As inductance varies directly with the square of the number of turns, this

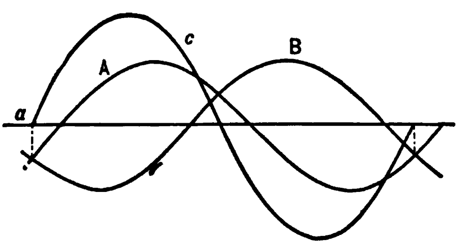


Fig. 34.

property can be much reduced without sacrificing efficiency or increasing the cost of the generator, by using fewer turns

per slot and more slots — in other words, the distributed form of winding.

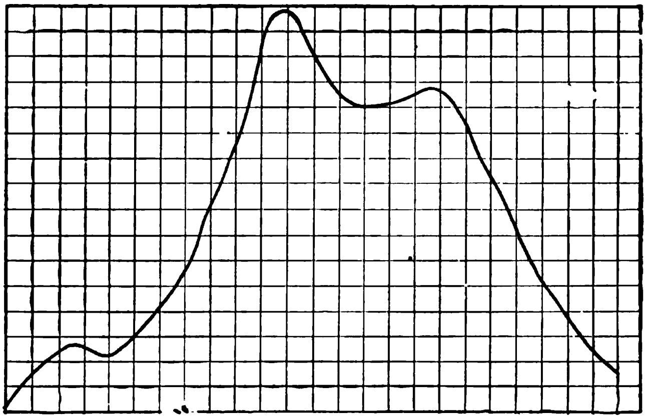


Fig. 35.

Armature reaction is greatest when the load is inductive, as then the phase displacement between current and *E.M.F.*

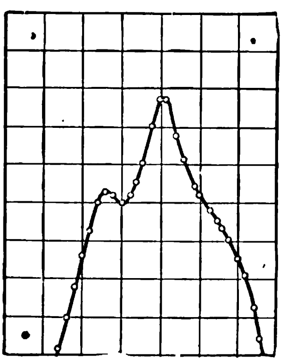


Fig. 36.

brings the maximum armature magnetism in the most favorable position for reacting on the field. The distrib-

uted winding minimizes the effect of armature reaction, because the separate portions of a coil constituting one phase do not occupy the same angular position with reference to the pole, and therefore the separate reactions produced by the separate sections of the coil give a resultant, not equal to their algebraic sum, but to their vector sum, which is less than their algebraic sum.

Since armature reaction produces a distortion of the field, a curve of *E.M.F.*, that may be a sine curve at no load, will often depart widely from this form when the generator is loaded. The distortion of the wave-shape in unitooth machines may be overcome in great part by careful shaping of the pole pieces.

While the armature reaction, due to a lagging current, lowers the terminal *E.M.F.* of a generator, a leading current may have the opposite effect by adding its flux to that of the field.

The relation between the *E.M.F.* induced in the separate armature coils and that delivered at the terminals of a three-phase machine with "Y" connected armature is shown in Fig. 34. Curves *A* and *B* represent the voltages measured between the common center and the ends of two of the three coils. Curve *C*, formed by uniting these "Y" electromotive forces, gives the so-called "delta" *E.M.F.*, or pressure between the outer terminals of the armature coils, and therefore the measured line voltage. In this way, if the line voltage is found to be 1732 volts, the voltage of any of the three coils with respect to the common center is $\frac{1732}{\sqrt{3}} = 1000$.

The electromotive force induced in the individual armature coils of a standard, "Y" connected, three-phase,

unitooth machine under full load is shown in Fig. 35. This *E.M.F.* is termed the "Y" *E.M.F.* of the machine.

The "delta" *E.M.F.*, or curve of pressure between any two of the machine terminals under the above condition of load, is shown in Fig. 36. This last curve can be readily obtained by adding two "Y" curves for any particular condition of load displaced 120 degrees.

CHAPTER III.

GENERATORS (Concluded).

Field Excitation and Compounding. — The voltage of a polyphase generator may be maintained uniform, under all normal conditions of balanced load, by varying the strength of the field excitation. Where the load is unbalanced the voltage of the more heavily loaded phases will be lower than that of the lightly loaded phases, and there are no means of equalizing in the generator an unbalancing of voltage between the phases due to unequal load conditions except by varying the number of armature turns in the phase to be adjusted, or by other equivalent means. Such means of equalizing the voltage are not commercially employed save in exceptional instances, because any differences of voltage are more simply and readily adjusted by means of separate devices known as potential regulators, usually inserted in the feeder circuit. These will be found described in another part of this book. In speaking, therefore, of compounding a polyphase alternator we mean the automatic process whereby the no load balanced *E.M.F.* and the full load balanced *E.M.F.* are made to bear any desired relation to each other. We speak of under-compound, flat-compound, or over-compound, according as the full load voltage is made to be less than, equal to, or greater than, the no load voltage.

Compounding devices are usually arranged to hold the

voltage constant as the load increases, or to raise the voltage to compensate for line drop. The amount of compounding desirable depends on the conditions, generators of good regulation operating under favorable conditions as to frequency and line characteristics requiring less than machines of poor regulation operating over a line where the drop is high. Moreover, with generators of small or moderate capacity compounding arrangements are, other things being equal, more necessary than with very large machines, for the reason that in the latter case the systems supplied by large generators are so extensive that increases of load in one section are more or less balanced by decreases of load in another. So that, at the power station, the resultant variation of load on the dynamos takes place slowly and can readily be compensated for by hand adjustment of the field rheostat.

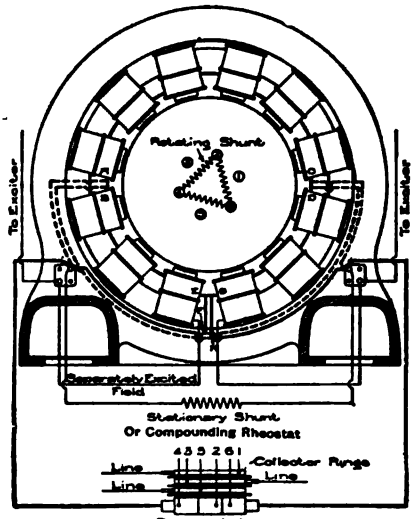


Fig. 37.

The early methods of compounding alternators followed the analogy indicated by the continuous current generator, and alternators were equipped with two separate field windings, one taking the practically constant excitation provided by the exciter, and the other connected in series

with the armature, a commutator being provided to rectify the current. To pass the entire armature current (duly rectified) through the series field coils was frequently found to give a greater than necessary series excitation, and in such cases only a part of the armature current was taken, a shunt resistance (located within the armature and re-

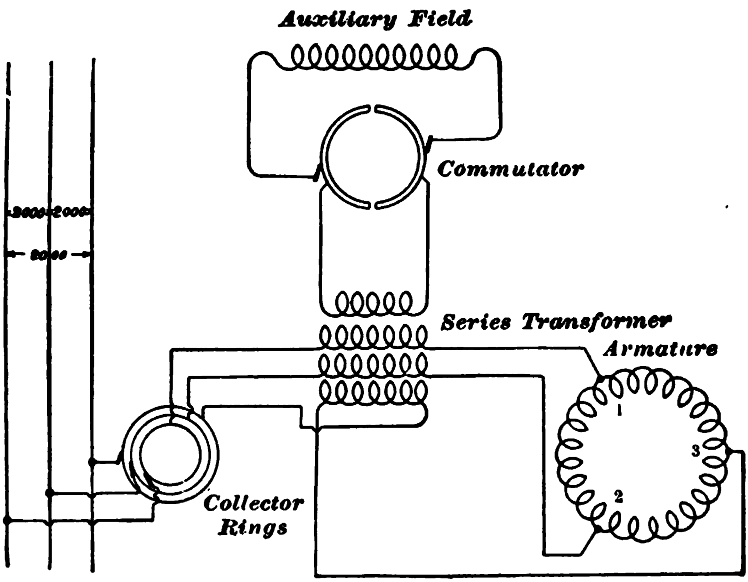


Fig. 38.

volving with it) being provided to divert any necessary amount. Another shunt, usually adjustable, external to the machine and connected in parallel with the series field winding, still further reduced the amount of current passing through the series coils and permitted the amount of compounding to be varied.

This method of compounding, applied, however, chiefly to revolving armature machines, was widely employed, and is embodied in large numbers of machines which are still in use.

The connections of a three-phase generator with compound field windings is shown in Fig. 37. A three-part commutator rectifies the currents from each of the three-phase circuits, so that unbalancing in any one line has a minimum effect on the regulation. The rotating shunt is practically the common center of the coil, giving a current in the series field due to about 1 per cent of the terminal voltage. The stationary shunt is adjustable, and can be varied for loads of different power factors. It also serves to prevent sparking at the commutator.

In another polyphase generator (Fig. 38) the low potential current for the series field is derived from a series transformer within the armature. All phases are represented in the primary. The compounding field current depends upon the sum of the currents flowing in the circuits supplied by the armature.

The demagnetizing effect, and consequent reduction of voltage, due to a load of poor power factor, has been explained. A generator so loaded requires a greater field excitation than when running on non-inductive load. The comparative voltages, with loads of varying power factor and the same excitation, are shown in Fig. 39. Curve *a* is the compounding when lights are the chief load, and *b* the curve when the load consists chiefly of motors. It will be seen that a generator properly over-compounded for a night load of lamps will not give the proper voltage for a

day load of motors. The stationary shunt in Fig. 37 will then have to be adjusted for the varying character of the load.

The method of compounding above described has the disadvantage that the series field coils usually have the same difference of potential above ground as does the armature winding; and where the armature is wound for a high potential the difficulty of insulation and the danger to life from accidental contact are correspondingly en-

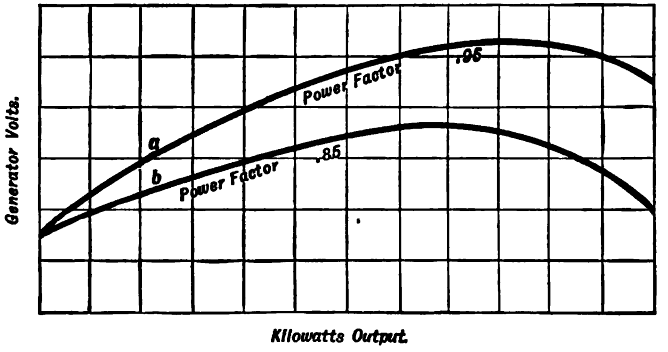


Fig. 39.

hanced. This method has the further important disadvantage that it does not automatically compensate for variations in power factor, since with a given value of the shunt resistances the current in the series field and hence the amount of compounding depends only on the magnitude of the current flowing in the armature, regardless of whether this is lagging, leading, or in phase with the *E.M.F.* For all modern construction, therefore, this arrangement has been virtually abandoned, particularly in view of the very perfect results that have been achieved

by methods that depend for their operation upon control of the exciter voltage, a method that will be fully described under the caption "Tirrill Regulator," a device by which any degree of compounding is easily secured regardless of power factor and regardless, too, within reasonable limits, of inequalities of speed.

The energy required to excite the fields of good commercial alternators on non-inductive load varies from about 1 per cent, in the case of generators of 500 kilowatts capacity and over, to 2, and sometimes 3 per cent in smaller machines. The energy for excitation is dependent also on the number of poles, for the reason that in a machine of given diameter a high number of poles means that the distance between poles is small and the magnetic leakage proportionately high.

The exciting dynamos are often driven from a pulley on the shaft of the alternator. The exciters are also often direct connected to their alternators, and where the alternator runs at high speed the cost of the direct-connected exciter is not excessive. In the case of very slow speed alternators, the cost of a direct-connected exciter is materially higher. Where exciters are driven either by belt connection or directly from their alternators, they are subject to the same speed variations as is the alternator. This, in turn, causes a variation in the exciter voltage, and the effect on the generator voltage is accumulative, conditions of low speed occurring simultaneously with low excitation potential so that the effect on the generator voltage is multiplied. With the improved compounding arrangements now obtainable these effects are minimized. Somewhat better operating conditions are provided, however, where the exciters are actuated from separate prime

movers, steadier excitation potential being thereby obtained. In water wheel plants this arrangement is obtained by equipping the exciters with independent water wheels. In the case of steam plants separate engines are provided for driving the exciters. Such engines are, however, usually of small capacity and realize only a moderate economy except in the largest stations, so that many steam plants derive their excitation from motor generator exciters in which the motor receives its current supply from the alternating current bus bars. With this arrangement a steam-driven set or a storage battery is necessary as an auxiliary to provide excitation when first starting up.

The use of motor-driven exciters is to some extent open to the same objections from the standpoint of voltage variation as exists where the exciter is belted or direct connected to its alternator. The speed variations of a motor-generator exciter do not, however, by reason of the inertia and high speed of its revolving parts, have the same magnitude as those of the main generators; and the superior economy of the motor-generator exciter has led to its wide adoption in steam-driven stations. Considerations of power consumption do not apply in hydraulic installations to the same extent as in those using steam; nevertheless, the motor-generator exciter, by reason of its simplicity and compactness, is frequently used in water-power stations. In such stations the motor-generator exciter has in some cases been provided with a direct-coupled water wheel, from which is obtained the necessary power at the beginning. After the main generators have been excited, the motor is switched in and provides the power for driving the exciter, the water-wheel governor thus practically shutting off all water from the water wheel.

This arrangement provides the advantage that in the event of stoppage in the water pipe, the entire load is taken by the driving motor, and vice versa, if current is cut off the motor, the water wheel picks up and the operation of the set continues without interruption. This arrangement, therefore, provides both a water wheel driven and a motor-driven exciter set without the use of two exciter generators, and insures, moreover, very steady speed and exciter potential over wide ranges of load, by reason of the combined action of the water wheel and motor, which divide the loads between them in a way to secure constant speed much more closely than could be secured by a water governor alone.

Regulation. — Regulation, sometimes referred to as inherent regulation, is defined in four or five different ways; but the now commonly accepted definition is the percentage rise of the voltage when full non-inductive load is thrown off, the generator speed and the field excitation remaining constant. From what has been said in connection with armature windings, it follows that, as a rule, generators with unitooth armatures will not have as good a regulation as the multitooth type. However, good regulation in these machines can be obtained at a slight sacrifice of efficiency, or by using more copper in the construction of the generator, and thus increasing its cost, or by the use of a high magnetic saturation of the iron, which increases the energy required for excitation. A certain three-phase unitooth machine of large output gave a regulation of 6¼ per cent, from full load to 10 per cent of the load. The same generator, when the load in one circuit was reduced 50 per cent, did not rise in voltage more than 5½ per cent; and with no load on one of the circuits, the

others being fully loaded, the greatest variation was 8 per cent. The standard belt-driven machines of the unitooth construction regulate within 8 per cent, which is close enough for satisfactory results to be obtained, even without automatic compounding. Generators of the multitooth construction require less compounding. The standard belt-driven machines of this type have a regulation of 6 per cent or thereabouts when designed for a frequency of 60 cycles.

On inductive loads the regulation, of course, is not so good. The generator mentioned above as having a non-inductive regulation of 6¼ per cent will require approximately 20 per cent more ampere turns in the field to give full load voltage when it is supplying current to motors on a circuit where the power factor is 80 per cent lagging. The regulation under these conditions is about 16 per cent. These results are immensely superior to those obtained with the old iron clad alternators, which often required 30 to 50 per cent increase in exciting current to maintain constant pressure even on non-inductive loads.

A construction involving poor regulation is sometimes intentionally used in generators designed for special purposes, for instance, in alternating arc lighting, where a constant current is required. Generators of poor regulation are sometimes used also in certain kinds of electric smelting where a constant energy output from the generator is required. The process is started at a certain voltage, and as the resistance of the external circuit decreases the terminal voltage falls in ratio to the increase of current.

Efficiency and Losses. — Fig. 40 gives the efficiency curves of a 3000 kilowatt three-phase water wheel-driven generator, and shows the individual losses in the machine. It will be noted that the highest efficiency is reached at

full load, and does not diminish up to 25 per cent overload, the losses at full load being only about 2.7 per cent of the total output. The efficiency at half load, 95.5 per cent, is most excellent. The loss due to bearing friction and to windage is constant at about two-thirds of 1 per cent for all loads. The I^2R loss in the field varies little from no load to full load, showing that the generator is easy to regulate. The core loss is practically constant, varying only from 38 kilowatts at no load to 38.5 kilowatts at full load. Other things being equal generators for engine connection will have an apparently higher efficiency than those otherwise driven, especially at light loads, as the friction losses are, as a rule, reduced by the omission of all bearing losses, these being considered as chargeable to the engine losses.

The efficiencies of generators, as usually given, do not include the losses in the exciter. As the exciter efficiency is from 80 to 90 per cent, and the field loss about 1 per cent, the reduction of the generator efficiency due to this source will seldom be greater than 0.2 per cent.

Power Factor. — Manufacturers' statements as to regulation and temperature of generators are usually given on the basis of 100 per cent power factor, i.e., 100 per cent energy load. Generators are constructed with reference to operation at the full rated current and voltage, i.e., voltampere output, at power factors as low as 80 per cent (80 per cent energy load). When operating at lower than 100 per cent power factor, the regulation is not as good. The regulation of standard alternators for rated voltampere output, 80 per cent power factor, is approximately:

25% in cases where it is stated as 10% at 100% power factor.
22% in cases where it is stated as 8% at 100% power factor.
18% in cases where it is stated as 6% at 100% power factor.

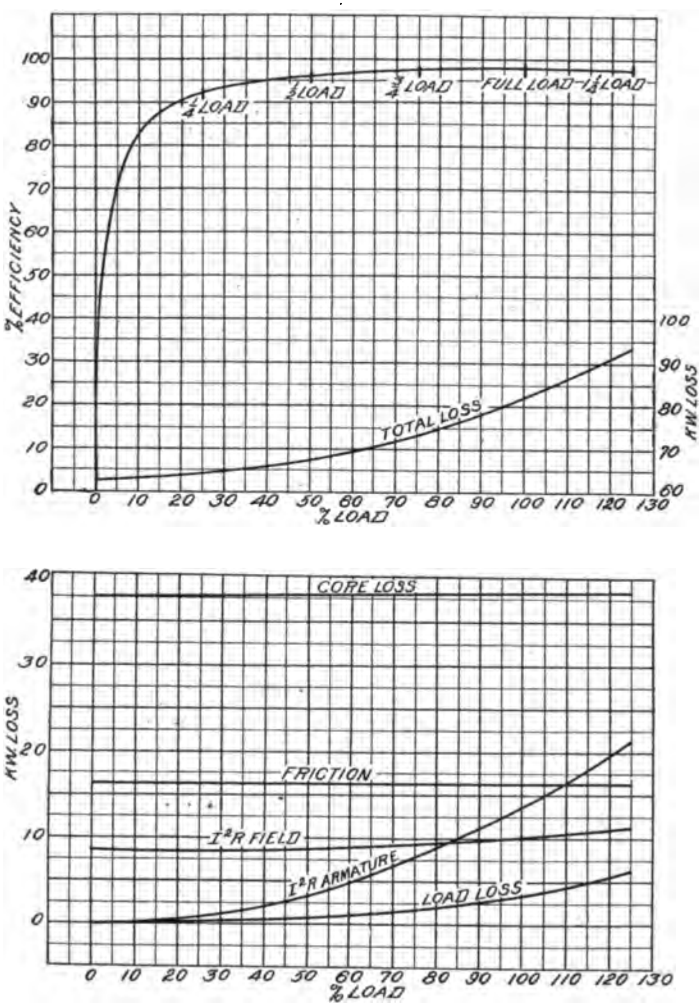

100
90
80
70
60
50
40
30
20
10
0
% EFFICIENCY
¼ LOAD
½ LOAD
¾ LOAD
FULL LOAD
1¼ LOAD
TOTAL LOSS
100
90
80
70
60
KW. LOSS
0 10 20 30 40 50 60 70 80 90 100 110 120 130
% LOAD
40
30
20
10
0
KW. LOSS
CORE LOSS
FRICTION
I²R FIELD
I²R ARMATURE
LOAD LOSS
0 10 20 30 40 50 60 70 80 90 100 110 120 130
% LOAD

Fig. 40.

The commercial efficiency of the average generator is about 1 per cent less for the 80 per cent power-factor load than for the 100 per cent power-factor load, both rated in voltamperes.

The result of operating at lower power factor is to increase the heating of the field coils due to the greater excitation required. This increase at 80 per cent power factor is about 5 degrees C. The temperatures as given for 100 per cent power factor are applicable for 80 per cent power factor to all parts of the several machines except to the field coils as noted.

Speed. — In nearly all classes of moving machinery — engines, water wheels, pumps, dynamos, motors, etc. — the weight and cost are lower when the apparatus is designed for high speed than when intended to run at a low speed. Generally the weight and cost go down as the speed goes up. Limitations to the saving attainable by increase of speed are found in the extreme mechanical stresses which are introduced at the higher speeds, these stresses imposing on the designer the use of costly materials or heavy sections in order to obtain the necessary strength of parts, or obliging him at increased cost to modify the electrical design in order to favor the mechanical. There is, therefore, for a machine of given capacity and characteristics a certain speed corresponding to minimum cost. It is not possible, except in special cases, to build generators commercially for this theoretically desirable speed, because the minimum cost speed for the generator may not coincide with the minimum cost speed of the prime mover. Moreover, conditions of operation may, and frequently do, demand the selection of a speed that is far from corresponding to minimum first cost. The choice

of speed, therefore, is fixed by a number of considerations in which the question of cost is only one. In alternating current generators and motors, furthermore, there exists an additional limitation in respect to choice of speed, namely, that imposed by frequency. Since frequency is a function both of speed and of number of poles, it follows that for a given periodicity the number of speeds available is confined to such values as will conform to the equation, $\text{Speed} = \frac{120 \times \text{Frequency}}{\text{poles}}$. Thus for a 60 cycle generator the highest possible speed is 3600 revolutions per minute, corresponding to a bipolar machine. The next lower speed is that corresponding to a four-pole generator, namely, 1800 revolutions per minute. For 25 cycles under similar conditions the speeds would be 1500 and 750 revolutions respectively.

In the older machines operating at 125 and 133 cycles, speeds of 1500 to 2000 revolutions were common. Such high speeds are disadvantageous in belt-driven designs, especially in the larger units, and to secure low speeds at these high frequencies required a design having a large number of poles, which in turn results in an expensive and inefficient machine. The advisability of more moderate frequencies was therefore indicated as being more suitable, both from the generator standpoint and from considerations of lower inductive loss in the external circuits. Various frequencies of relatively low magnitude have become standardized, each chosen with respect to the conditions to be met, and frequencies above 60 cycles are now rare save in the older plants. The majority of polyphase belt-driven generators in actual use in this country are wound for 60 cycles, while on the Continent

and in England the prevailing frequency is 50 cycles. The standard belt-driven generators constructed by one of the largest manufacturers have the following number of poles and speeds for the respective outputs when designed for 60 cycles:

K.W.	Poles	R.P.M.
50	6	1200
75	8	900
100	8	900
150	12	600
200	12	600
300	16	450
450	20	360
650	20	360
750	24	300

The alternating-current generator is far from being like a direct-current machine — a flexible piece of apparatus in respect to speed. The speed cannot be altered more than about 10 per cent either way from that for which it is designed, without appreciably affecting the constants of the generator and of the apparatus to which the generator is supplying current.

Parallel Running. — In modern alternating-current plants parallel operation is necessary in order to effect a reduction in the number of circuits and transmission lines. Other advantages are economy, simplicity, and reliability of operation. Polyphase generators, as now designed, can be operated in multiple without any difficulty.

The principal requirement in the generators is that they shall have a moderate armature impedance and a uniform air gap. Too small an impedance permits an excessive exchange of current with slight inequality of the field excitation of the machine, and a dangerous flow if the generators are connected up when they are not quite in

step. Generators having a large armature impedance will operate in parallel; but, owing to the small synchronizing current that can be exchanged, the condition is not stable, and the generators are liable to lead alternately in speed or " hunt."

When generators are run in parallel the field excitation must be adjusted on each to that value which would give the same voltage if the machine were operating alone. If this is not done, lagging currents will be taken by the armature of that machine whose field is too strongly excited, these lagging currents acting to correct the over-magnetization by opposing the flux which the field coils produce. Conversely, those machines that are under-excited will take leading current. The result is that idle currents, possibly of large magnitude, circulate between the machines and through their armature windings, overheating the conductors or reducing the effective output which for the same temperature rise could otherwise be obtained. With proper adjustment of excitation these idle currents disappear. When this condition is attained the sum of the readings of the ampere-meters of the several generators will be equal to the total amperes delivered to the external circuits. The same condition is indicated when the generators are found, by means of suitable instruments, to be delivering their respective outputs at the same power factor, taking into account the fact that the power factor of all generators will have the same sign, i.e., all generators delivering lagging current, or all delivering leading current, or all working at unity power factor, according to the character of the load.

The requirements for the prime mover are uniform speed and uniform angular rotation. In belt-driven generators

the pulleys must all have the same dimensions. The belts must be watched to see that they do not slip. These two points must be especially observed in generators driven from the same shaft. The speed regulation of engines operating direct-connected alternators in parallel is discussed in the following section. Water wheels and steam turbines have an absolutely uniform angular rotation, and are the best prime movers for parallel running.

Synchronism of two polyphase generators is determined by some form of phase indicator. A common arrangement consists of two transformers, the primaries of which are connected to each generator, care being taken that the connections are made to similar phases. The secondaries are connected in series with one or two lamps in circuit. With the transformer secondaries connected in a certain relation, the machines are in synchronism when the lamps cease to glow. If the secondary of one transformer is connected in the opposite sense, synchronism is indicated when the lamps are at their maximum brilliancy. This latter connection is preferable because the instant of maximum brilliancy is susceptible of fairly accurate determination, whereas with the transformers connected for synchronizing "dark" the operator must rely on his judgment to determine the instant of time lying midway between the moment when the lamps cease to glow and when they begin to glow again. As soon as synchronism is indicated by the lamps, according to one or the other of the two above methods, the machines may then be thrown in parallel by the main switches. Where alternators are equipped with series fields, the commutators must be connected by an equalizer to place the series windings in multiple. The connections and station instruments required

for the process of throwing generators in parallel and operating them continuously, as used extensively in this country,

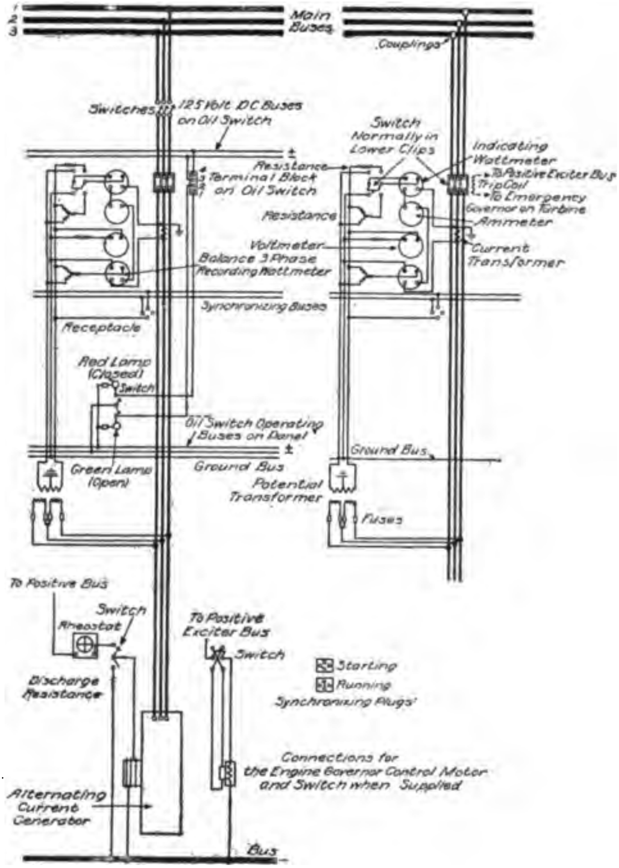


Fig. 41.

are shown in Fig. 41. This figure shows the type of generator more commonly built at the present time, that is, one having separately excited field winding only.

It does not follow that because one phase of a polyphase circuit is synchronized, the other phases are ready for parallel connection. It is necessary that when a number of machines are first installed for operating in parallel, the connections should be such as to give the same phase rotation in all the machines. The circuits can be tested out, for proper connection, by means of two sets of phase lamps.

In the diagram (Fig. 42) temporary transformers are

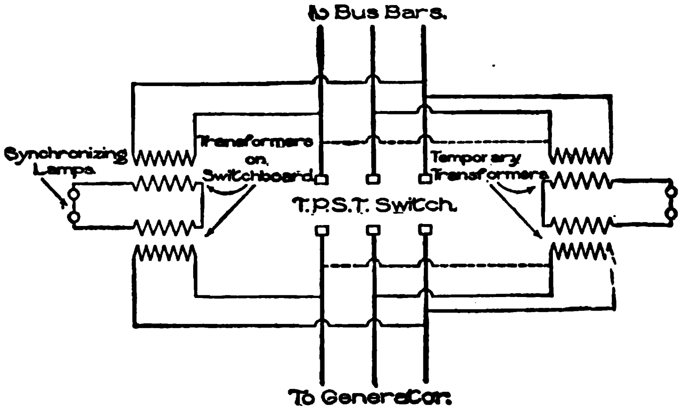


Fig. 42.

shown connected to a different phase of the circuit from that in which are the permanent lamps. Connection should first be made with the outside blades, as shown by the dotted lines, to prove that the two sets of lamps become alight and are extinguished at the same time. By the separate connections of the temporary transformers, it can be ascertained if the machines are properly connected to

the synchronizing switches. The connections are correct when both lamps are simultaneously dark or simultaneously bright, according to whether the secondaries of the transformers are connected in the manner shown by the figure, or whether in connecting them in series one of the secondaries is connected in the reverse sense.

With the continual increase in the size of units it was appreciated that more perfect means of synchronizing were desirable than those provided by the lamp arrangements just described, for the reason that more serious consequences ensue if large generators having heavy revolving parts are switched in out of phase. Such a device is provided in the synchronizer or "synchroscope." This device consists essentially of a small single-phase induction motor, of which the stator is excited from the station bus bars and the rotor excited by split-phase currents from the alternator which is about to be synchronized. A revolving field is thus produced in the synchronizer and the rotor will revolve at a speed which is governed by the difference between the frequency impressed upon the stator and that impressed upon the rotor. To the rotor shaft of the synchronizer is attached a pointer, which, at first revolving rapidly, will revolve more and more slowly as the frequency delivered to the rotor approaches that delivered to the stator. When the frequency is the same in each member the velocity of the rotating field will be zero and the pointer will be stationary. This condition indicates equality of frequency, but not necessarily correctness of phase. For the latter condition there is but one relative position of stator and rotor in which the flux generated by stator and rotor is simultaneously in the same direction; hence, while equality of fre-

quency is indicated by a stationary position of the pointer at any angle, the machines are in phase only when the pointer is stationary in a predetermined position (usually pointing vertically upward). In other positions the angle occupied by the pointer indicates the instantaneous difference of phase between the machines.

From what has preceded it will be apparent that a meritorious feature of this device is its ability to indicate whether the generator which is being synchronized is running too fast or too slow, because if running too fast the frequency impressed upon the rotor will be greater than that impressed upon the stator and a progressive forward rotation of the pointer will result. Conversely, if the generator being synchronized is running under speed, the pointer will have a retrograde motion. Synchronizers of this type (which have the general appearance shown in Fig. 43) provide the means of determining correctness of phase with the utmost nicety, and are widely used where accurate synchronizing is desired.

Fig. 43.

Speed Regulation of Engines. — Steam engines intended for direct connection to alternators which supply current to rotary converters or to synchronous motors, or which are operated in parallel, should be designed to have an angular rotation as nearly uniform as possible. Otherwise the oscillations in the relative motions of the generators or of the generators and synchronous apparatus may produce an excessive exchange of currents — a state of

affairs known as "hunting," "pulsation," "pumping," or "surging."

The amount of deviation from the position of absolutely uniform angular speed permissible for satisfactory work depends upon a number of conditions. It is affected by the design of the generator, and rather more by the difficulties of operating synchronous apparatus. For the majority of cases it is customary to specify an allowable angular variation of about $2\frac{1}{2}$ degrees of phase from the mean. This means that in engines direct connected to alternators of $2n$ poles the position of each revolving part should not differ more than $\frac{2\frac{1}{2} \text{ degrees}}{n}$ in circumference from the position it would have at absolutely uniform rotation. Thus, in a 40-pole alternator the maximum allowable deviation from the position of uniform rotation would be $\frac{2\frac{1}{2}}{20}$ or $\frac{1}{8}$ degree of circumference.

The above expresses the regulation of the engine as a deviation in position from that of absolutely uniform rotation in degrees of total circumference measured, for example, on the circumference of the fly wheel.

Single cylinder or tandem compound engines cannot, as a rule, give as good results as engines whose cranks are quartering.

The difficulty of parallel operation of alternators is not, however, very often due to the cyclic irregularity of the turning moment of the prime mover (which, by changing the frequency during each revolution, may cause hunting of synchronous apparatus). Nor has the design of the alternators any material influence upon their successful parallel running. It was demonstrated some years ago,

under conditions where all the requirements of uniform angular velocity had apparently been complied with and it was still impossible to keep the generators satisfactorily in step, that a condition of perfect stability in parallel operation was secured by applying anti-hunting governors to the prime movers. Where the engine governor acts very freely the impulses due to changes of load are emphasized and the governors tend to overrun or hunt. The cure is in the use of a dashpot device which will retard for a brief period any motion of the valve mechanism, but which will yield to continued pressure, thereby preventing sudden jumps in speed while still allowing the governor properly to control the steam admission with variations of load.

Another, although rare, condition liable to prevent satisfactory parallel operation is sometimes found where a generator of exceptionally close regulation is connected to an engine whose revolving parts, including the rotating member of the alternator, are of such weight and operate at such a speed of rotation as causes the number of engine impulses to coincide with the natural period of oscillatory vibration of the entire reciprocating and revolving parts considered as a torsion pendulum swinging on either side of the point of synchronism. This fact becomes important with generators of close regulation, owing to the large value of synchronizing current which passes when the machines get out of step, and the tendency of this large current is not only to pull the machines back into synchronism, but to cause the lagging machine to overrun and become leading with respect to the other. In doubtful cases careful calculation will indicate the probability, or otherwise, of this action, which can be guarded against

by a change or rearrangement of the weights so as to alter the so-called natural period of vibration.

Methods of Driving Generators. — The method of driving a generator from its prime mover is determined mainly by the size of the generator and the type and speed of the prime mover. Polyphase units up to 200 kilowatts are usually belted, unless the prime mover consists of a water wheel of high speed, or special conditions favor direct connection to an engine. The mechanical arrangement of a small belted generator is shown by Fig. 44. The yoke rests on, and is sometimes an integral part of, the bedplate, which also supports two bearings. The pulley is overhung.

The method of belt-driving larger units is shown in Fig. 45. The bedplate is extended, and carries a third or outboard bearing which partly relieves the inner bearing of the belt strain and the weight of the pulley.

Generators designed for water-wheel connection are usually provided with bedplate, shaft, and two bearings. These machines are self-contained for the more perfect alignment of the bearings. Fig. 46 illustrates the general arrangement of generators of 500 kilowatts capacity and above. A half-coupling is provided, which is machined to a close fit with the other half furnished with the water wheel.

Generators for direct connections to engines are built without bedplate, shaft, or bearings. The yoke rests on a thin iron soleplate supported by a suitable foundation. The engine bearing serves also for the inner bearing of the generator. The outboard bearing rests on a separate cap. It is usually furnished with the engine, and is of a design uniform with the inner bearing. The engine shaft ex-

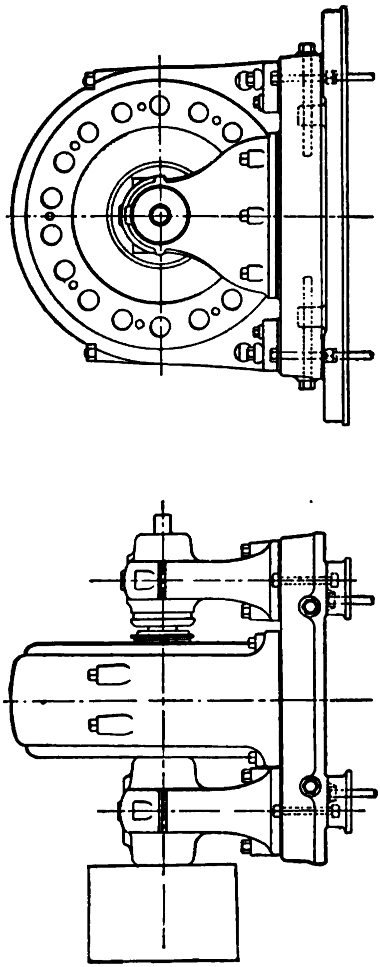


Fig. 44.

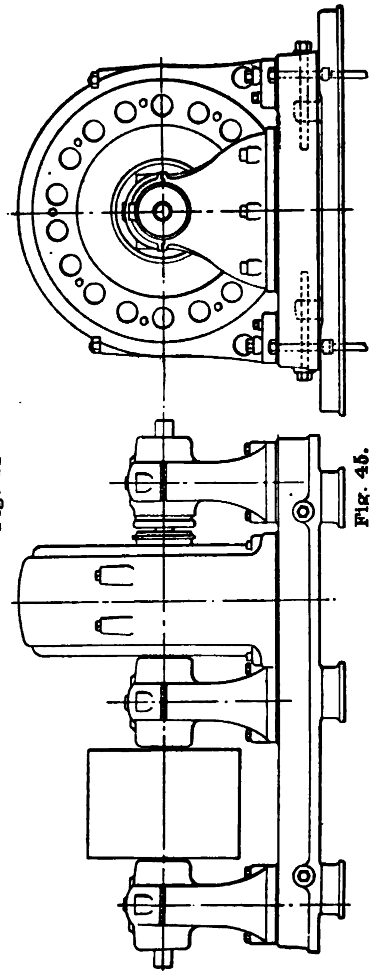


Fig. 45.

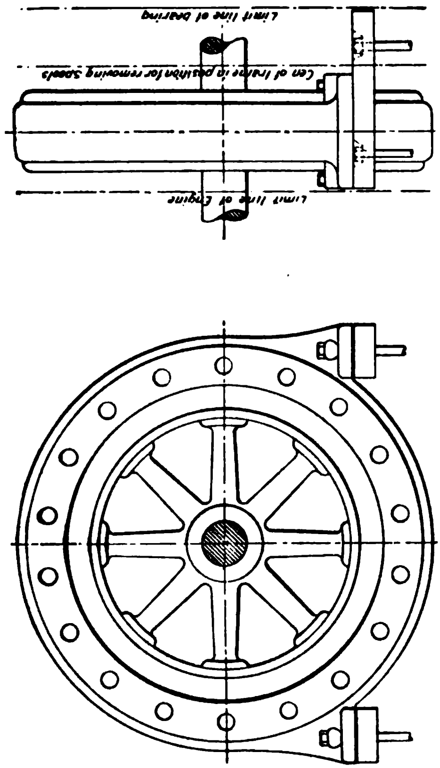

Limit line of bearing
Cen of frame in position for removing spools
Limit line of Engine

Fig. 47.

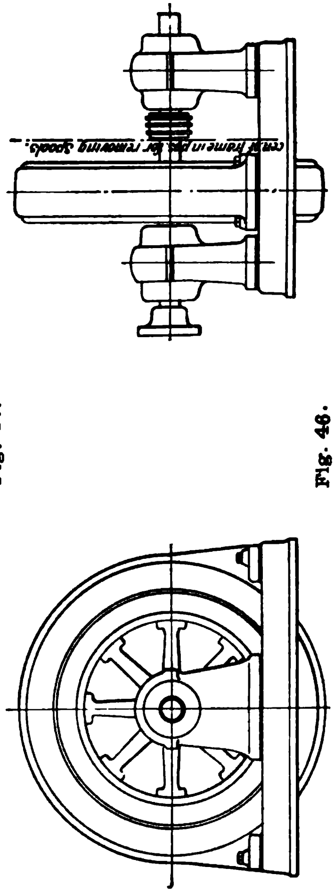

cen. of frame in pos. for removing Spools.

Fig. 46.

tended carries the revolving element of the electrical unit (Fig. 47).

Polyphase generators above 500 kilowatts should preferably be direct coupled to the prime mover. The method of driving large generators by belts or ropes necessitates a large extension of the base and a heavy pulley, and is mechanically awkward. This method of driving may be used in exceptional cases, as, for instance, in connection with a wheel plant already installed, operating under a very low head at a low speed. The increased cost of extended shaft, outboard bearing, and pulley will, however, go far towards offsetting the increased cost of a slower speed generator, for direct connection, which does not require these parts.

Polyphase generators are direct connected to water wheels either by a vertical or by a horizontal shaft. While most generators in this country run from horizontal shaft turbines, the advantages of the vertical shaft construction, particularly for large units, are causing a wider adoption of this form. These advantages lie in the saving of floor space, which means a smaller power house, and in more responsive wheel regulation. The shaft is out of sight, the stresses on the shaft are practically those due to torsion only, which permits a smaller shaft to be used, and the appearance of the unit is as a whole most pleasing. The principal disadvantages operating to prevent a wider use of this type were, first, an anticipated difficulty (which has been overcome) of properly supporting the weight of the shaft with its revolving parts, and, second, the fact that the vertical type is not quite so accessible for inspection and repair. The advantages named have, however, caused the adoption of this type in many important installa-

tions, among which may be mentioned several of the power stations at Niagara Falls, the large hydraulic station of the Mexican Light and Power Company at Necaxa, and the plant of the Great Northern Power Company at

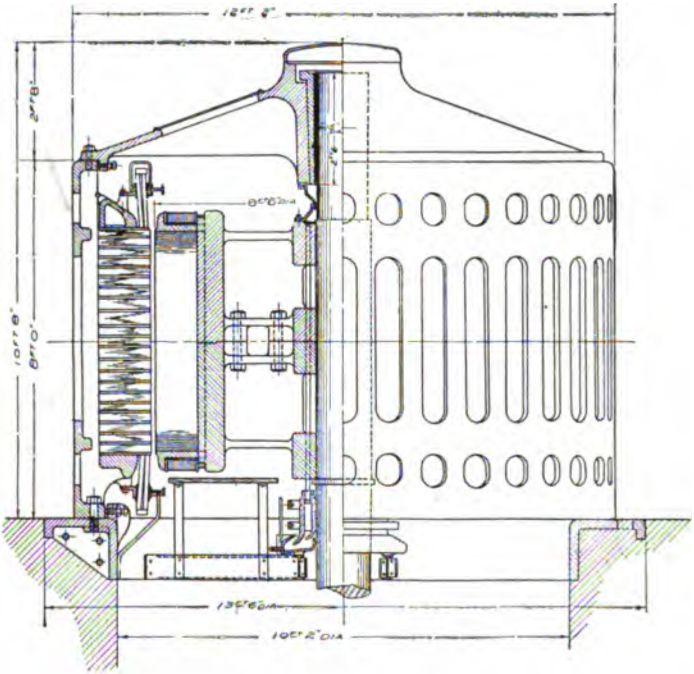


Fig. 48.

Duluth, Minnesota, which has been laid out for an ultimate capacity of eight machines, each of 7500 kilowatts.

Fig. 48 shows the typical construction of most large vertical shaft generators. The machine illustrated is of the revolving field type, eight poles, 7500 kilowatts, 375 revolutions per minute, 6600 volts, 25 cycles.

In the horizontal type sometimes a shaft extension and outboard bearing is used, the water wheel, properly housed, occupying the space between the inboard and outboard bearings. Such an arrangement is peculiarly adapted for use with impact wheels and provides an arrangement whereby perfect and permanent alignment of bearings is secured. Machines of this construction are used in the power plants of the Big Cottonwood Electric Company; the Pioneer Electric Company, Ogden, Utah; and the Southern California Power Company, Redlands, Cal.

More often the generator is equipped with but two bearings and is driven by the water wheel through a coupling. This construction is followed in the 3000 kilowatt generator depicted in Fig. 26.

Where engines are direct connected to polyphase generators it is customary for the electrical manufacturers to furnish the machine without shaft, base, or bearings. For the same speed, therefore, engine-driven generators are cheaper than those driven by water wheels. It must not be forgotten, however, that engine speeds are limited by a number of conditions, while water wheels are practically limited in speed only by the head obtainable.

Fig. 49 illustrates a three-phase generator of 1200 H.P. capacity, direct connected to an engine running at 94 revolutions per minute.

This generator is direct coupled to a Corliss type of engine of 1300 indicated horse power, running at 94 revolutions. It has 32 poles, and gives a current at 5000 volts and a frequency of 25 cycles. The armature windings consist of 96 coils, three for each pole, or two slots per phase per pole. The windings are Y connected. The field coils are flat strip copper, 1 inch by $\frac{1}{16}$ inch, wound on

edge, and insulated by intervening layers of paper. As the exciting current has a pressure of not greater than 120 volts, the potential at the terminals of each field spool is about four volts. The efficiency of the generator is

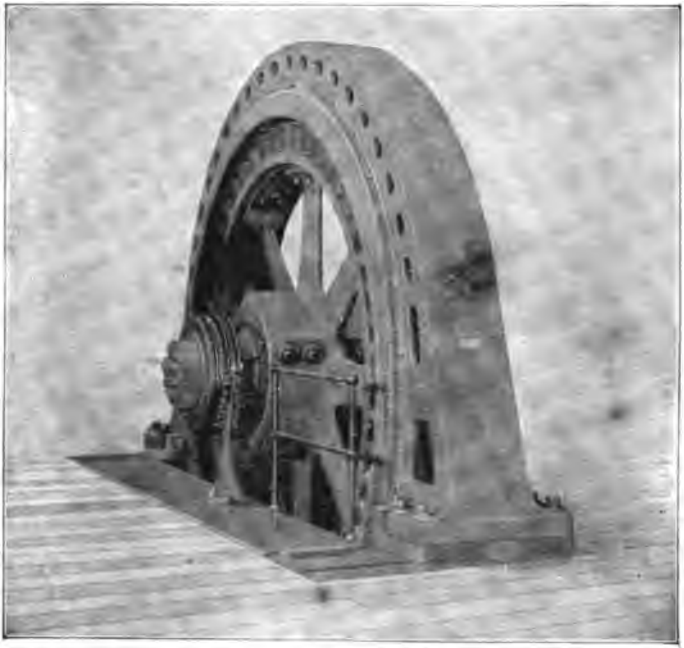


Fig. 49.

95½ per cent at full load, 94½ per cent at three-quarter load, 92½ per cent at half load, and 87 per cent at quarter load. The regulation on non-inductive load is 6 per cent, and the exciting current about 120 amperes.

Engine-driven generators are sometimes constructed with their field magnets built out as integral parts of the engine

fly wheel, they with their windings being fastened to the external periphery. These machines are known as Fly-wheel Alternators. The largest machines of this type yet constructed were designed by the Westinghouse Company for the Manhattan Railway Company of New York. They have a nominal rating of 5000 kilowatts with 50 per cent overload capacity, height 42 feet, diameter of revolving part about 32 feet, weight 185 tons. The revolving field construction consists of a steel hub which supports a dovetailed structure of steel web plates which form the driving spider. The field poles and rim are built up with overlapped plates of thin sheet steel, the length of each plate being equal to two poles. The plates are dovetailed into the driving spider, and the rim and poles with their steel end plates are separately bolted together. In the body of the field poles, at intervals of about 3 inches, ventilated spaces or ducts are provided. These spaces extend inward to the laminated steel rim of the fly wheel to large openings in the cast-iron driving rim. The ventilating ducts in the revolving field register with corresponding ducts in the external stationary armature. The field-pole tips are beveled at the edges to produce a magnetic distribution of such a form that with a star type of three-phase winding the *E.M.F.* wave will be practically a sine wave at no load. The speed is 75 revolutions per minute, poles 40, frequency 25. The field requires 225 amperes at 200 volts when the machine is delivering its rated current at 11,000 volts on a non-inductive load. About 15 per cent more current is required when the armature delivers its full rated output at normal voltage to a circuit having a power factor of 90 per cent. The regulation is such that if load of 263 amperes per phase, 11,000 volts, and with

100 per cent power factor be thrown off, the potential will rise not more than 6 per cent; field excitation and speed remaining constant. It is calculated on non-inductive load, that the efficiency will range from 90 per cent at quarter load to 96½ per cent at full load, mechanical friction not being included.

Polyphase generators, designed for driving by steam turbines, present certain special features of construction by reason of the high rotative speeds at which they operate. The same features of construction are to a certain extent used in the design of generators for direct connection to extra high speed water wheels. The distinguishing characteristic of these extra high speed machines is the ratio of length to diameter, which in some cases may be equal to unity or even greater, whereas in machines for more moderate speeds the length is almost invariably but a small fraction of the diameter. The restriction of diameter follows from the necessity of keeping the peripheral speed within practicable limits. Even with the small diameters chosen the peripheral velocity reaches in some designs as high as 12,000 feet per minute. Even at these speeds the diameters, relatively speaking, are so small that a considerable length is required in the armature in order to provide the requisite quantity of irón. Machines of smaller weight for the same capacity would result could the armature diameter be increased, but such a course is prohibited by considerations of peripheral velocity.

The high rotative speeds imposed from considerations of turbine design, ranging from about 3000 to 1800 revolutions in machines of 500 kilowatt capacity, to about 750 revolutions per minute in the largest sizes, require, for all of the commercial frequencies, a small number of poles. Even

at the lowest speeds turbine generators for 25 cycles usually have but four poles. The values chosen for the densities in the copper and iron circuits are not substantially different from those appropriate to slower speed

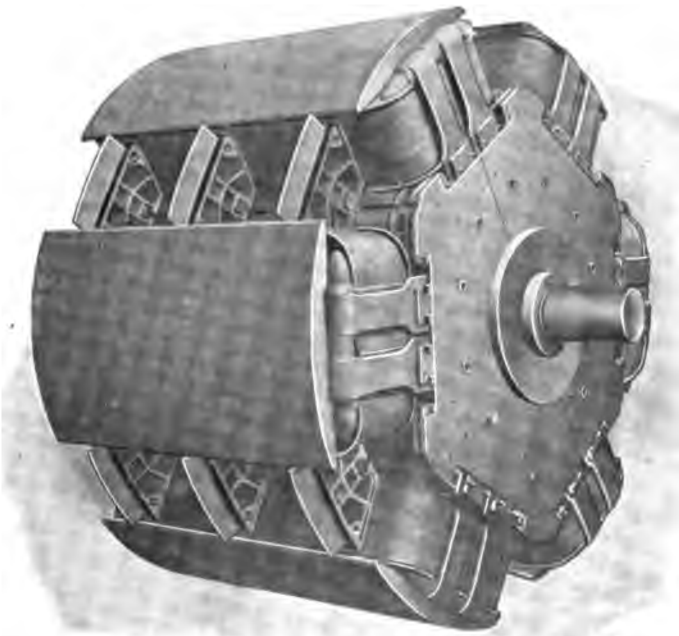


Fig. 50.

designs, although by the nature of the case the ratio between iron and copper losses is somewhat higher in turbine generators than in ordinary designs. This means, in effect, that a turbine generator is one having relatively small copper losses, and, consequently, one in which the

overload capacity and overload efficiency are high, which is found to be the case.

Fig. 51.

Considerations of strength and of perfection of balance in the rotating parts are of prime importance. These are obtained by the choice of the strongest materials, used in

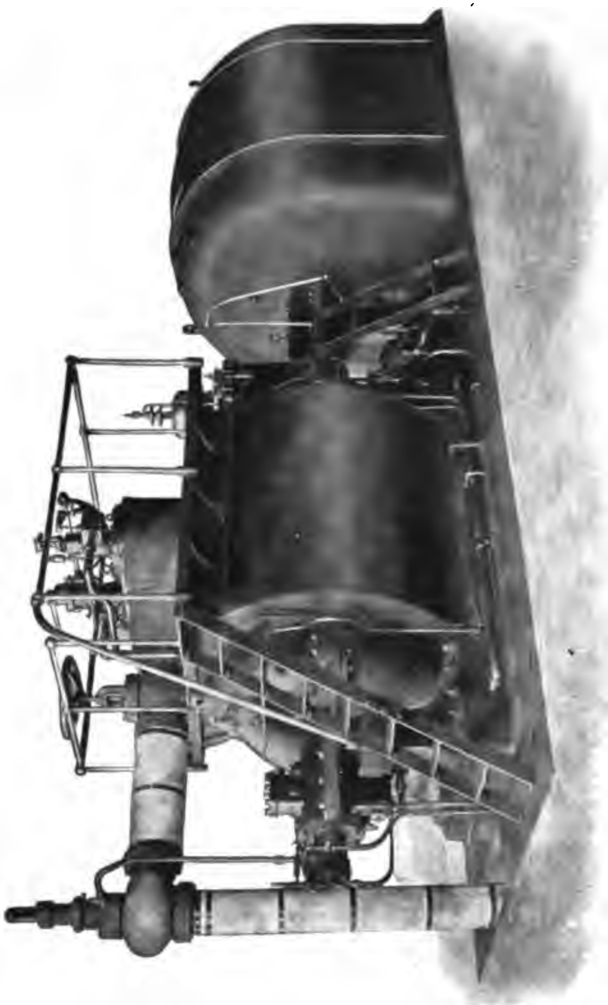


Fig 52.

ample sections, and by the exercise of the greatest care in machining the parts. Fig. 50 shows one form of construction of the revolving part (in this case the field) of the turbine alternators manufactured by the General Electric Company. In this type the revolving part is built up of sheet steel laminæ, about $\frac{1}{8}$ inch thick, symmetrically assembled around a central spider. The field coils embody the familiar edgewise winding and are held in place by the projecting pole tips. Wedge-shaped retainers are also provided between the sides of adjacent spools, these retainers being securely keyed in place.

In the stationary element the armature coils are placed, in the customary way, in the slots with which the core is provided, and supported by an arch-like binding band structure at the ends. This alternator, conforming to the turbine standards of the General Electric Company for all except the smaller sizes, is of the vertical shaft type, the shaft being supported by a step bearing in the base of the turbine, which is located beneath the generator. Fig. 51 is representative of the type of Curtis turbine set manufactured by this company.

The turbine alternators manufactured by Parsons, Westinghouse, Brown-Boveri and most other manufacturers, employ the horizontal-shaft design. In the machines manufactured by these companies the rotor is usually machined from a steel casting, the poles being solid and the armatures being of the closed slot type with the windings threaded in by hand. Fig. 52 shows a typical turbo-alternator of the Parsons type as constructed by the Westinghouse Electric and Manufacturing Company. Figs. 53 and 54 illustrate respectively the stationary armature and the revolving field of a similar alternator.

Conditions Affecting Cost. — From what has preceded it will be easily understood that the first factor in determining the cost of a polyphase generator of given capacity and conditions of operation is its speed. The initial

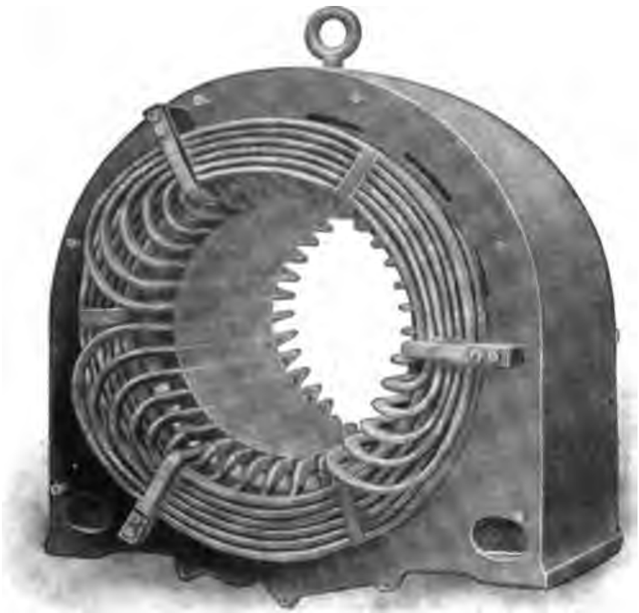


Fig. 53.

voltage is another factor, and likewise the efficiency, frequency, the regulation, and the temperature rise. A generator wound for high voltage may, under certain conditions of proportion and design, cost more to construct than a low voltage machine of the same characteristics

together with a complement of step-up transformers. A generator of high efficiency can be built at a reasonable cost but at some sacrifice in regulation. Conversely, the same generator may be designed for better regulation at the sacrifice of efficiency, and cost no more. This is for the reason that machines having close regulation must be designed with small armature reaction, which means the use of liberal iron sections and increased cost, or on the other hand, with high iron densities, which means larger core losses and excitation losses and consequently a poorer

Fig. 54.

efficiency. To obtain both these constants in an eminent degree requires a liberal use of both copper and iron and results in an expensive machine.

The frequency for which a generator is designed also influences the cost. For a given output and speed and for the same constants of operation, low frequency machines will require considerably more copper in the armature and somewhat less copper in the field, the total copper required in the machine being practically the same in either case. The labor item is usually lower in a low frequency machine because on the average it costs less to wind, say, ten

large coils than twenty small ones, even though the weight is the same in either case. On the other hand, the amount of armature iron required in low frequency generators is larger, because with the diminution in the number of

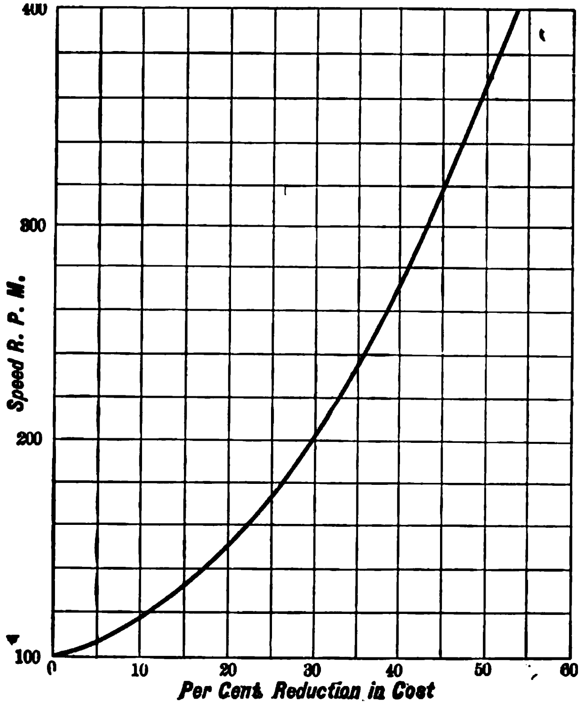


Fig. 55.

poles the amount of flux to be carried by the armature is split up into fewer paths and the cross section must consequently be proportionately larger. This condition reaches its extreme in the case of bi-polar alternators, such as those of medium capacity for direct connection to steam

turbines, where the section of armature iron must be sufficient to carry one-half the entire flux generated by the field winding. Iron, however, is cheap as compared with the price of labor, so that on the whole a machine of low frequency will cost somewhat less, other things being equal, than one of high frequency. The proportionate saving incident to reduction in frequency is more noticeable in the lower speeds, such as are used with direct-connected engine-driven units. The differences are not great at the medium speeds, or in belt-driven generators, or in generators that are provided with parts that remain the same irrespective of the frequency. In the highest speeds the low frequency machines will be heavier and more costly, largely by reason of the extraordinary amount of armature iron which has to be provided where the number of poles is very low.

Fig. 55 shows in an approximate degree the relative reduction in cost with increasing speed. In using this curve for comparison of costs, it must be kept in mind that it is only approximately correct and applies to generators of the same type, frequency, general constants, and conditions of operation, and that it does not extend far enough to show the point at which, as, for example, with high speed turbo-alternators, an increase rather than a decrease in cost is involved by further increase of speed.

CHAPTER IV.

INDUCTION MOTORS.

Principles of Operation. — The induction motor can be compared to a direct-current shunt motor, the essential difference being that the armature or working current of the shunt motor is led into it by brushes, while the working current of the induction motor is an induced or transformer current. The windings of the induction motor, connected to the supplying circuit, besides carrying the exciting current, have the additional function of supplying the transformer current. The induction motor is thus seen to combine the principles of operation of both a motor and a transformer. Rotation may be considered as being produced by the revolving member following a shifting magnetic field which is the resultant of two or more alternating fields differing in phase. The explanation of the working of the induction motor by reference to the rotating magnetic field alone, however, is apt to mislead and to hide its true functions.

The two elements of an induction motor are preferably designated as primary and secondary, and sometimes as field and armature. Either may be indifferently the rotor or stator.

When running without load, the rotor speed is very closely that of the rotating field, and there is a very small current induced in the secondary. The magnetic

pull of this current on the field produces a feeble torque. The current taken by the primary member, or field, is then composed of the magnetizing current and that required for overcoming magnetic and mechanical friction. As the power factor is low at light loads, being not more than 15 or 20 per cent in most commercial motors, the energy supplied is not much greater than that consumed by a shunt motor of the same capacity.

When running under load, the speed of the revolving element falls away from that of synchronism, and the *E.M.F.* and working current induced by the relative cutting of the lines of force, increase with the difference in speeds. The pull of this increased current on the field produces a powerful torque. The departure from the speed of synchronism is called the "slip," and, within certain limits, is proportional to the total secondary resistance.

To insure high efficiency and good regulation, the resistance of the shunt motor armature must be kept as low as practicable. For the same reason, the windings of the secondary of the induction motor should have a low resistance.

Methods of Starting Motors. — On connecting an induction motor to its supplying circuit, there is an excessive rush of current, which can be prevented only by the use of some device external to the motor windings proper. There are a number of such arrangements for reducing the starting current of motors.

One, and probably the most common device, consists essentially of a variable resistance, which can be cut in or out of circuit with the secondary winding. When the secondary element is the rotor, this resistance often occupies a space within the armature spider. When so located

it may consist of copper strips, or — as is usually the case — of iron cast into a compact grid form, having a number of contact points. The whole of this resistance is in series with the secondary winding at starting. As the motor attains speed, a circular short-circuiting switch, mounted in a ring encircling the shaft, is pushed centrally by a lever, thus cutting out the resistance in as many successive steps as there are contact points. Motors provided with this starting device are usually designed to start with a torque ranging from 75 to 150 per cent of full-load torque. This motor has the desirable characteristic that the current is very nearly proportional to the torque from starting to full-load speed.

The rheostat is frequently external to the motor. With this arrangement, when the secondary revolves, collector rings are required to convey the induced current to the rheostat. When the primary is the revolving element, collector rings are also needed to supply the main current to the motor.

A water rheostat is sometimes employed, by means of which the induced current is varied, its strength varying with the depth to which the plates are immersed. With this device, the current taken by the motor is closely proportional to the torque, from starting to full-load speed.

Another method of starting induction motors consists in reducing the impressed volts by the use of some form of reactance or of compensator coils, or of resistance in the main circuit. A compensator is the most efficient means of cutting down the voltage, and the most generally employed, one coil being required for each phase.

The connections of a popular starting device for two-

phase motors are shown in Fig. 56. Two compensator coils, or auto-transformers, are provided, one for each phase. A cylindrical switch, like that in the familiar street car controller, having segments of proper width and spacing, acting in conjunction with a set of stationary contact fingers (M, L_1, A_1, A_2, etc.), effects the proper

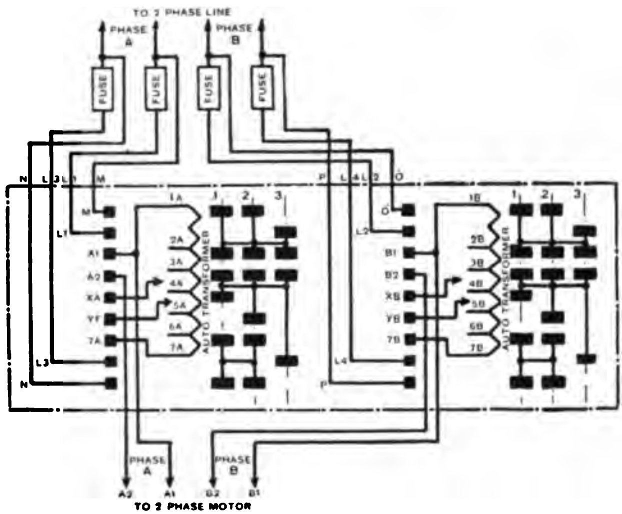


Fig. 56.

circuit combinations during starting. The salient feature of this type of starting device is that the voltage is applied to the motor in three steps, first a low potential, then a medium potential, and finally full potential. Additional taps are brought out from the compensator coils for the purpose of varying the values of the two starting voltages.

The connections of a starting compensator for a three-phase motor, as made by another American company, are

shown in Fig. 57. In this design there is but one step between the "off" and the "running" position. The necessary circuit combinations are effected by cylindrical switch segments and stationary contacts of usual form, and extra taps are provided in the compensator coils for varying the starting voltage. In this make of compensator, when used with motors of 15 H.P. and under, there are three taps with voltages 40 per cent, 60 per cent, and 80 per cent of full voltage. For motors above 15 H.P. four taps are provided, at 40 per cent, 58 per cent, 70 per

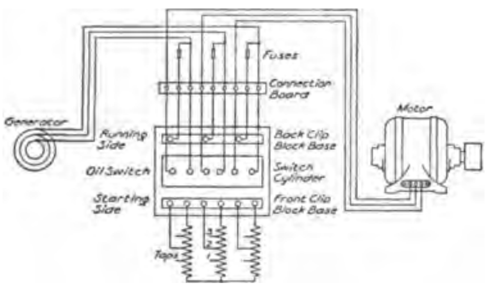


Fig. 57.

cent, and 85 per cent of full voltage. The selection of the proper tap voltages is determined by trial, according to the amount of starting torque necessary for the motor to have under operating conditions, and when once adjusted no change is required. In both types the compensator switch serves also as main line switch, the motor terminals being "dead" when the compensator is in the "off" position. Separate line switches are therefore unnecessary.

In both the diagrams it will be noticed that two leads are provided in each phase on the compensator connection

board. This is for the purpose of by-passing the fuses so that the possible large currents taken at starting will not cause the automatic cut-outs to act, the circuit being so arranged that when the compensator is in the running position the fuse is cut into circuit. The switch connections are such that the compensator coils are disconnected as soon as the running position is reached. This is done not only to prevent needless waste of energy in the form of iron and copper losses in the cores and windings of the compensator, but also to prevent overheating of the device. Since the coils are intended to be in circuit only during the short periods corresponding to the time required for starting, they do not need to be designed to radiate continuously the amount of heat represented by the combined core losses and I^2R losses. With this in view it is possible during the starting periods to work both the iron and copper at very high densities such as would result in a burnout were the coils left continuously in circuit. It is accordingly necessary to disconnect them from the circuit as soon as the motor has reached full speed, and the connections of the starting switch are devised accordingly.

Induction motors which are put in operation by the first method, may be designated as the variable resistance-in-armature type. They frequently have a higher self-induction, and in the rotor require more copper and more iron. The secondary winding is definite and polar, and the additional iron in the rotor is necessitated by the fact that, owing to the space taken up by the insulation of the rotor bars, the slots are wider and deeper, which results in a greater total depth of iron. The polar winding indicates also the reason for the higher self-induction of this

type, which is remediable by increasing the number of slots — in other words, by making the rotor winding as distributed as possible. This feature, in turn, narrows the teeth slightly, and by thus increasing the density, tends to enhance the core loss and to diminish the power factor. A low total resistance being necessary in order to keep down the slip, it follows that a liberal cross section must be chosen for the rotor windings of this type by reason of the increased length of turn which the longer end connections impose. The total rotor copper is therefore large, both by reason of the total length of copper employed and by reason of its large cross section.

Motors which are used with the compensator starter may be designated as the compensator, or short-circuited armature type. Their distinctive feature is the short-circuited armature, which is usually of the squirrel-cage construction. This construction gives a low self-induction to the rotor and thus to the whole motor, thereby insuring large maximum output. In this type the amount of rotor iron is a minimum, and the core losses small by reason of the narrower slots that can be used. The end connections are extremely short, and the cross section of rotor bar small, so as to provide sufficient resistance to insure fair starting torque, so that the rotor copper as a whole is of small amount.

In either type the construction of the stator is practically the same, both as to amount of material and to design.

In starting an induction motor with variable secondary resistance, precaution must be taken that the resistance is all in, otherwise the flow of current may overheat the motor or overload the lines. The armature lever should

be pulled out as far as it will go; then the line switch may be closed, and, finally, the short-circuiting switch may be slowly closed. The motor should be handled at starting to reach full speed in about fifteen seconds. As the secondary resistance is of a capacity only to start the motor, it never should be left in circuit or used to regulate the speed of the motor. The motor is shut down by first opening the line switch and then open-circuiting the armature resistance.

As the drop in a good transformer on a lighting load is within 3 per cent, and on an inductive load, as motors, seldom less than 5 per cent, it is advisable to always use separate transformers for lights and for motors. The exception to this rule is in a secondary system of distribution, where the motor load is a proportionately small part of the entire load.

Induction motors are sometimes started by being connected directly to the supplying circuit without the use of any form of starting device. Such a motor will, of course, take a large starting current. This can be kept down by making the resistance of the armature conductors rather high, and by confining the motor to work requiring a small starting torque. A motor started in this way should not be used on circuits where the effect of a large starting current on the potential regulation of the system is of importance.

The direction of rotation of a three-phase induction motor is reversed by reversing any two of the leads, and of a two-phase motor by changing the two leads of either phase.

Construction of Primary and Secondary. — The simple and substantial construction of the induction motor is one of its chief advantages, resulting in a minimum cost of

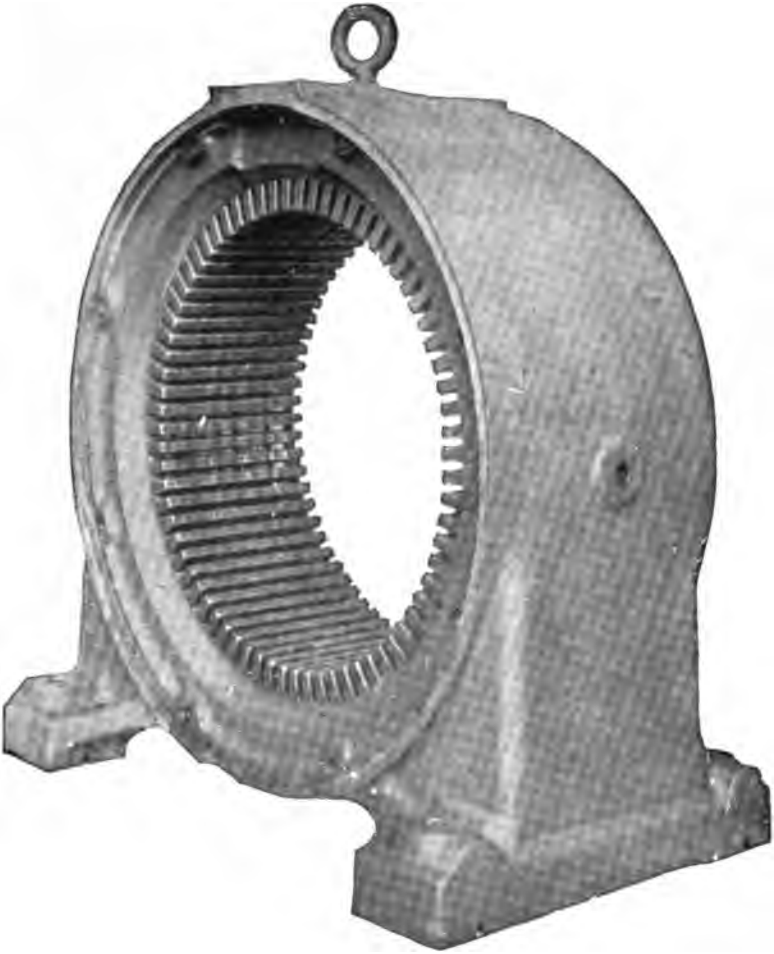


Fig. 58.

maintenance and attendance. While either element may be the rotor, by far the larger number of commercial

motors are now constructed with a fixed primary and with a rotor secondary.

The fixed primary is similar in construction to the stationary armature of a revolving field generator with multitooth winding.

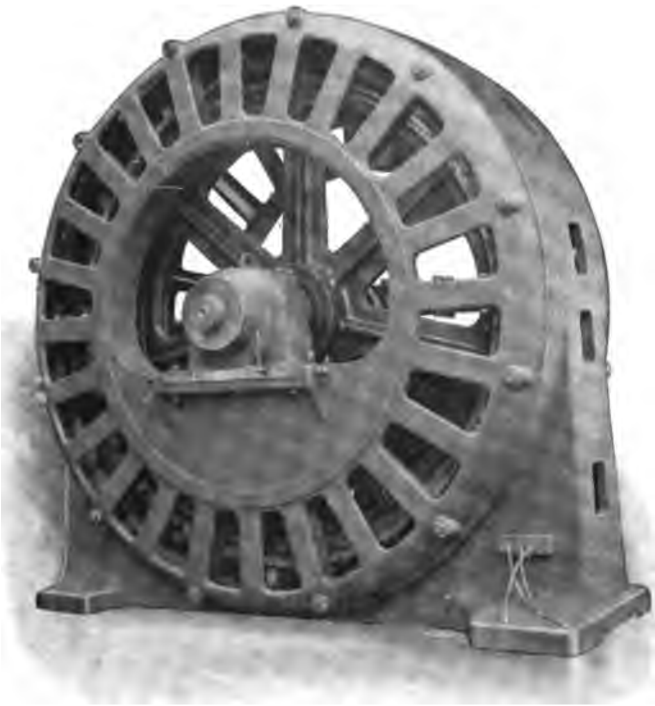


Fig. 59.

It is built up of slotted laminations mounted on a cast-iron spider. The coils are imbedded in the slots. Fig. 58 illustrates the primary or field ready to receive its con-

ductors. These stationary windings are usually protected from mechanical injury by end shields, which frequently support the bearings. The Westinghouse Company employ this form of construction in even the largest sizes, as illustrated in Fig. 59, which represents an 800 H.P. motor of the short-circuited armature type.

This motor is wound for 60 cycles and 2000 volts, it has 36 poles, hence a synchronous speed of 200 revolutions per minute.

In most motors made in this country the stator punchings are provided with open slots (as shown in Fig. 58) and use form wound coils, a construction which reduces the labor of winding and which enhances greatly the convenience of repair. The closed slot construction however decreases the reluctance of the magnetic circuit and thus, by reducing the magnetizing current, betters the power factor. This construction is widely used abroad where lower labor costs offset the extra expense of hand winding. It is also employed in special instances in this country where, for example, in high voltage motors the width of slot demanded by the insulation would in the open-slot construction prevent the attainment of satisfactory power factors except at prohibitive expense in other directions.

The rotor armature of the standard form of motor has a laminated slotted structure similar to the primary. In motors of the variable resistance type, the secondary has a definite series of coil windings, corresponding to the polar windings of the primary. Since motors of the variable resistance type may have the resistance internal to the rotor and revolving with it, or external to the rotor, the rotor windings in the latter case are brought out to slip rings from which are led by brushes the currents passing

to the stationary rheostat. Motors of the short-circuited type are generally wound with copper bars laid in the slots and connected at both ends by short-circuiting metal rings. Secondaries of this construction are termed squirrel-cage armatures.

Fig. 60 shows the elements of a 50 H.P. motor of a standard make, the photograph illustrating the stationary primary or stator and showing the variable resistance type armature with collector rings for external rheostat.

Fig. 60.

In the motor at one time manufactured by the Stanley Company (Fig. 61) the field is stationary. There are, in reality, two fields and two armatures. The secondary windings are connected so that the wire lying under the field poles on one armature is in series with the wire lying between the poles on the other. The field coils are staggered, each half alternately playing the part of a motor and transformer.

Starting Torque and Current. — At normal voltage certain types of motors possessing a moderate secondary

resistance — as, for instance, a motor of the variable resistance type, with the resistance cut out — will have a small starting torque due to the reaction on the primary of the excessive induced secondary current. The starting current consumed by the motor will likewise be excessive.

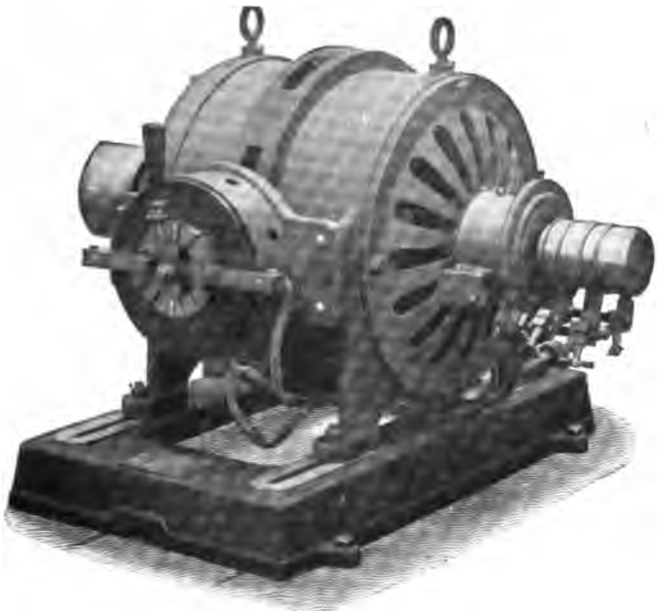


Fig. 61.

At nearly synchronous speed such a motor will have a powerful torque. By increasing the secondary resistance, the starting torque is raised until a critical resistance is reached, beyond which point the starting torque decreases.

The starting torque of an induction motor is also dependent upon the potential applied at its terminals. The

starting current is reduced by lowering the voltage, but at the sacrifice of the torque at starting, which varies as the square of the impressed voltage.

An inspection of the curves in Fig. 62 will show how the starting torque is influenced by varying the secondary resistance. The secondary winding of the motor is

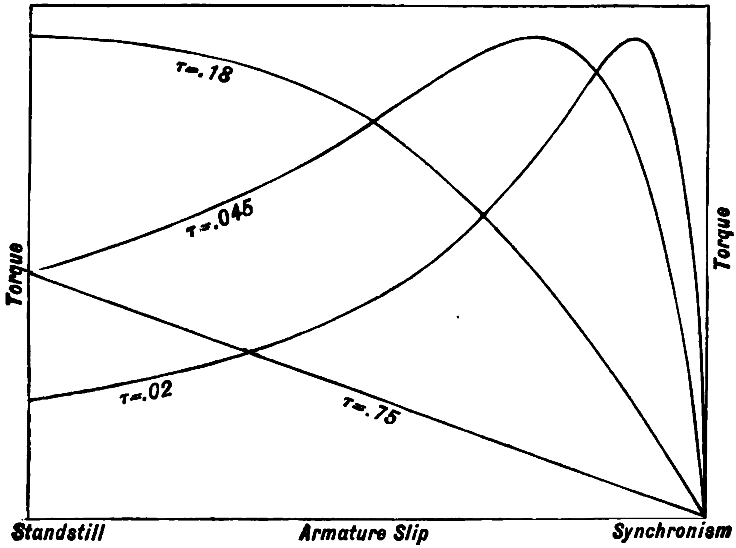


Fig. 62.

assumed to have a fixed resistance of 0.02 ohm. At starting, a variable resistance is connected in series, making a total of 0.18 ohm. The corresponding torque is about 25 pounds, or 150 per cent of full-load torque. When the motor reaches about 50 per cent of synchronism, part of the resistance is cut out, making the total 0.045 ohm. The torque now increases until about 85 per cent of synchro-

nous speed is reached, when it begins to drop. At this point the remaining resistance is short-circuited, leaving only the resistance of the secondary. The torque, due to this resistance, 0.02 ohm, reaches its maximum at about 90 per cent of synchronism. The starting torque, with a secondary resistance of 0.02 ohm, is about 7 pounds. The starting torque, due to a resistance of 0.75 ohm, is less than when the total secondary resistance is 0.18 ohm, being only 16 pounds. The current in the primary of such

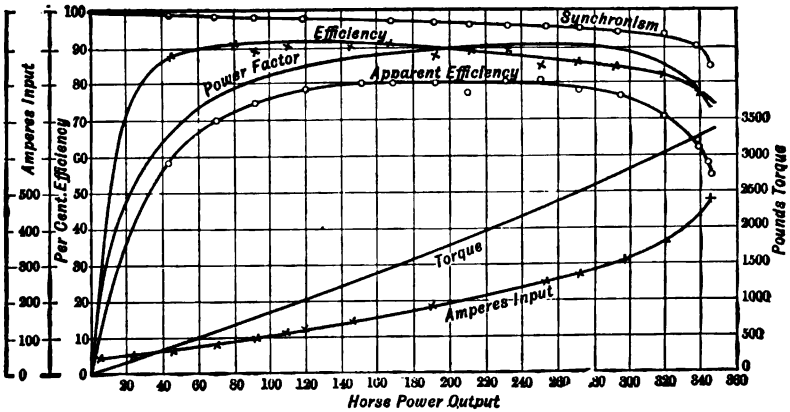


Fig. 63.

a motor at all speeds will be nearly proportional to the torque developed. At the moment of cutting out the successive resistances, the current will momentarily increase in strength. It can be readily seen that, by using a sufficient number of resistance steps, the motor could be brought up to speed with uniform torque and current. When the motor is taxed beyond its capacity, its torque and speed rapidly diminish and a large current will flow. This breakdown point is determined by the design of the motor, and

is usually chosen at from 50 to 100 per cent greater than the rated load. The working point of such a motor is on the descending portion of the power curve, at about two-thirds of the maximum output. Curves of torque and amperes input at all loads, of a 175 H.P. motor, are given in Fig. 63. The maximum torque which a given motor can deliver is a constant. The speed at which this maximum torque occurs, however, depends upon the value of the rotor circuit resistance, as shown by the curves in Fig. 62.

The magnetizing current which is characteristic of most alternating-current apparatus, such as transformers, induction motors, etc., has the effect of increasing the full-load current and putting a greater demand on transformers, line, and generators. The total current is greater than that actually required in supplying the losses and doing the work of the motor. The ratio of this working or energy current to the total current gives the power factor.

As the starting current of the motor, with short-circuited armature, is reduced by lowering the voltage, it follows that, for the same starting torque as that developed by the variable resistance type, the current will be considerably greater.

The line starting current and the torque of some makes of motors with short-circuited armatures, expressed in percentages of full load, are about as follows:

E.M.F.	Starting Current from Line.	Starting Torque.
40%	112%	32%
60%	250%	72%
80%	450%	128%
100%	700%	200%

The local current between the compensator and motor will be greater than the line starting current, as its poten-

tial is lower. The action of the compensator is similar to that of a transformer.

By increasing the resistance of the armature of these motors, the starting current for the same torque is decreased; but the result is an increase in the slip, and a loss of efficiency which may be as great as 2 or 3 per cent.

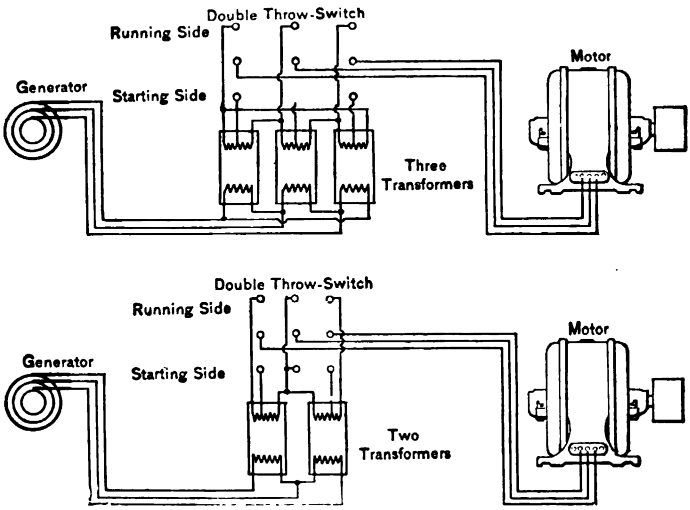


Fig. 64 and Fig. 65.

Where transformers are used for individual motors, or where several motors are located close to, and operated from, a bank of transformers, it is sometimes practical to bring out taps from the secondary winding, and use a double throw motor switch, thereby making provision for starting the motor at low voltage, and saving the cost of a compensator. The connections of such an arrangement are shown in Fig. 64 and Fig. 65.

Motors of the variable-resistance type have a special range of usefulness when operated from circuits requiring good regulation such as is demanded in central station work. They are desirable for service where high starting torque at moderate current input is required.

Fig. 66.

Fig. 66 represents a 50 H.P. three-phase motor of this type, and shows at the left the lever which actuates the short-circuiting switch of the internal resistance.

The short-circuited type is to be recommended for power circuits, and when the motors must be started from

a distance and simplicity of operation is of moment. It is adapted for service calling for low starting efforts and continuous running, and is especially advantageous when the motors are apt to run overloaded, or on circuits of unsteady voltage. It is not adapted for lighting circuits, where good regulation is important, unless the current at starting is small when compared with the capacity of feeders and generators.

Speed Regulation. — Absolutely synchronous speed is never attained in an induction motor, as some slip is required to furnish the current consumed by the light-load losses. Under increasing load the speed will fall away from synchronism until the break-down point is reached, and if the motor is not relieved of its load it will come to a standstill. The current will then be at its maximum. The fall in speed from that at light load to that at normal rated load will vary in some types of induction motors from 1½ per cent, as in motors of 100 H.P., to 3 per cent, as in smaller motors. Motors constructed with high and fixed secondary resistances may drop in speed as much as 9 per cent.

The complaint has been made against the induction motor that it is an inflexible piece of apparatus in respect to regulation of speed. It is quite true that wide variations of speed are obtained in modern motors only at the expense of efficiency and increased cost of construction.

There are a number of methods of obtaining a variation of speed in an induction motor.

The method now most employed is that by rheostatic control. A resistance is intercalated in the secondary circuit, which can be varied by short successive steps. The range of speed usually demanded of a variable speed

induction motor does not permit the use of the small resistance, such as is used in starting in some designs of motor, and which is located within the rotor armature. An external rheostat is required of sufficient size to dissipate a considerable amount of energy. Fig. 67 shows the connections of a three-phase motor and of a rheostatic controller for variable speeds. Collector rings, as shown, must

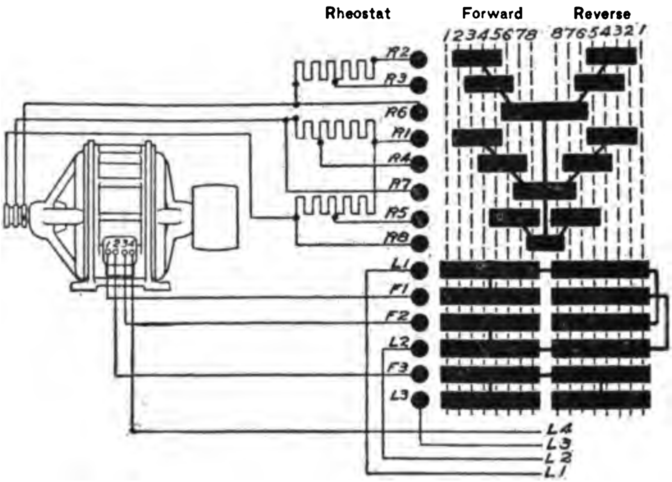


Fig. 67.

be added to motors having revolving secondaries for electrically connecting the windings and external resistance.

The main line is shown as passing through the controller. By this arrangement the circuit is closed simultaneously with the commencement of the operation of cutting out the resistance. It is in appearance similar to the well-known street car controller, and, like it, is reversible. Even when all the resistance is cut out it will be seen that there is still some loss of energy in the cables leading

from the collector rings to the controller. Where the motor is to run for considerable periods at full speed and it is desired to eliminate these external I^2R losses, a separate device may be provided to short-circuit the collector rings at the motor after the external rheostatic resistance has been short-circuited. Such a device is also sometimes equipped with an arrangement which at the same time lifts the brushes off the collector rings, thereby eliminating also the small but constant losses which would otherwise exist by reason of I^2R and friction in the brush contacts.

When two motors are employed together in the same class of service, as for instance in polyphase railway work, the speed may be reduced one-half and less by the method of concatenated or tandem control. This method consists in feeding the secondary of one motor which is connected to the supply circuit direct to the primary of the second motor. The motors are not necessarily of the same construction, but must be provided with collector rings and brushes. The secondary current of the first motor furnishes power to the second motor instead of being dissipated in a rheostat, thus directly increasing the efficiency of the first motor. The secondary current of the second motor is regulated by a resistance in circuit. A speed lower than half is obtained by increasing this resistance. A higher speed is obtained by connecting the motors in parallel on the supply circuit with their secondaries feeding into regulating resistances. The tandem method of control lowers the power factor of the first motor and, thereby, its torque. The speed-controlling mechanism is somewhat complicated.

A water rheostat for varying the secondary resistance,

and, correspondingly, the speed, of the motor, is used by Ganz & Co. in a three-phase railway plant in Northern Italy. The general form of this rheostat is shown in Fig. 68. Compressed air is admitted below the bottom of the tank, raising it, and thus increasing the depth of immersion of the metal plates.

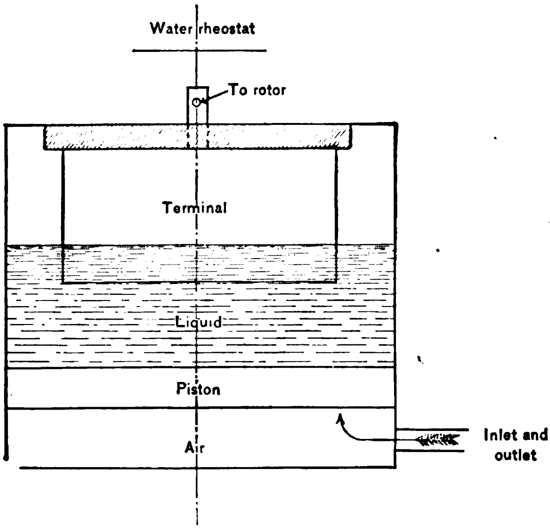


Fig. 68.

A more elaborate construction of the water rheostat is employed with large stationary motors, as for instance in large hoisting work, where the magnitude of the energy to be dissipated is such as to demand special arrangements for cooling the rheostat. In this form the tank which contains the electrodes and the solution is provided with an auxiliary pump which continuously circulates the elec-

trolyte through coils of piping cooled by water. A supply of compressed air controls the height of the liquid and thus the depth of immersion of the plates, or the plates may be raised and lowered manually. A liquid rheostat of this type, manufactured by the Allgemeine Elektricitäts Gesellschaft, is used with a large induction hoisting motor supplied by that company, the connections and arrangement being shown diagrammatically in Fig. 69. The rheostat is shown at *D* in the lower left hand of the diagram together with its circulating pump, which is of the centrifugal type. The letters on the diagram refer to the following parts:

A Emergency switch.
B High tension fuses.
C Reversing switch.
D Liquid rheostat.
E Main controller lever.
F Controlling lever for speed.
G Brake lever.
H Depth Indicator.
J Foot-controlled emergency brake.
K Speed varying gear.
L Lever for *K*.
M Electro-magnetic brake.
N Transformer for supplying current to brake and to pump motor.

Other Methods of Speed Variation. — The speed of an induction motor can also be controlled by changing the impressed voltage at the motor. This method requires the use of an external reactance or a compensator, and a motor possessing a high fixed armature resistance.

The controller and compensator are usually separate. By a sufficient number of taps in the latter, connected by cables to the controller, a graduated variation of the impressed voltage is obtained, and a corresponding variation in speed. This method finds only a restricted application and is even then usually confined to motors of but small capacity. It has a special field of usefulness where traveling cranes are equipped with polyphase motors, for by it the number of sliding contacts by which the

current is led to the hoisting and cross-travel motors is halved.

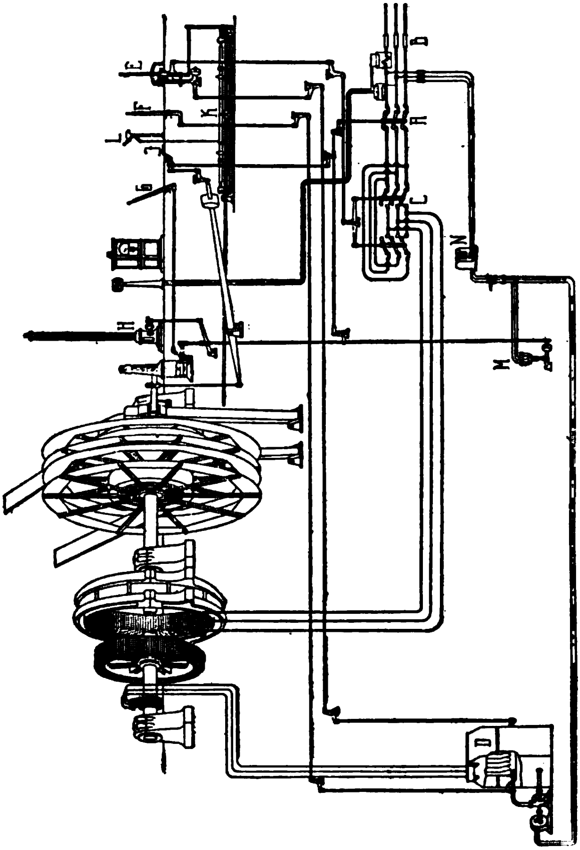


Fig. 69.

Another method of controlling the speed is by changing the number of poles. When a variety of speeds is required, this method is complicated, requiring, in addition

to a compensator, an elaborate switching device. It is objectionable also, as the motor can only run at full, one-half, and one-quarter speed, and at no intermediate speeds. This method has been successfully employed in cases where half speed and full-load torque are required, and has the advantage, not possessed by other methods, that it yields a fair efficiency at half speed, there being no wasteful rheostat losses.

An investigation of the relative efficiencies and power factors of induction motors of 10 H.P. output, equipped with the rheostatic and with the potential, variable speed-controlling devices, gives the approximate results shown in the following table:

Speed.	Method of Control.	Efficiency.	P. F.	Ap. Ef.
Full	Rheostatic	83	86	72
	Potential	83	86	72
Half....	Rheostatic	41.5	86	36
	Potential	36	57	20.5
Quarter .	Rheostatic	21	86	18
	Potential	16	48	7.7

The torque is assumed to be constant at all speeds.

In practice it will be found that, in order to give the best all-round results, the motor for potential control will have a lower efficiency at full speed than the motor built for rheostatic speed control.

The motor with rheostatic control shows the same power factor at all speeds.

The potential control gives a lower power factor and efficiency at all but full speed.

The motor controlled by change of poles will be found to be the most efficient for half and quarter speeds, and has the highest power factor except at quarter speeds.

Of the commercial methods of obtaining speed variation, that by potential control is inferior to the rheostatic control in point of efficiency. A drawback to the rheostatic method is that the motor requires collector rings.

Ilgner System. — A special application of the speed control of induction motors intended to run with a large but variable slip is afforded in the type of induction motor generator set used in the Ilgner system. In order to reduce the fluctuations of load incident to severe duty of highly intermittent character, such as occurs in hoisting work, and to secure economical results in current consumption at fractional speed running, recourse is had to the well-known Ward Leonard scheme of control. By this scheme, as applied to alternating-current working, the hoist motor itself is of the direct-current type, its current supply being derived from a motor generato set, the economy of the system resulting from the fact that a variable voltage is applied to the terminals of the hoist motor by means of variable excitation on the direct-current generator. Full-load current, and thus full-load torque, can thus be imparted to the hoist-motor at any desired speed, and since there are no rheostatic losses the energy taken from the alternating-current mains is proportional only to the useful work done. This arrangement, even taking into account the fixed losses in the motor generator set, results in a high economy of energy, though it does not reduce the magnitude of the maximum demand, and still throws back on the feeders or on the generating station the fluctuating characteristics pertaining to hoisting service.

In the system devised by Ilgner the motor generator set, the direct-current hoist motor, and the Ward Leonard control are retained, the feature of novelty being the introduction of a heavy fly wheel as part of the motor generator; and the function of this fly wheel is to absorb surplus energy at times of minimum demand and to give it out at times of maximum demand, in this way equalizing the input taken by the motor generator set.

Since there can be no increment nor decrement in the energy stored in a rotating mass except by change of speed, and since, further, the speed of the motor-generator set, with fly wheel, if driven by a motor of ordinary design would vary only within narrow limits (as fixed by the usual magnitude of the slip), it follows that the slip of the motor in an Ilgner set must be high enough to insure a speed range of adequate amount. In these sets the maximum slip is usually fixed at about 16 per cent, and as the loss of energy represented by this degree of slip is considerable, an external rheostat is used, commonly of the liquid type in the case of large units, the rotor of the induction motor being polar wound and equipped with collector rings in the usual manner.

Fig. 70 illustrates the equalization of power demand secured through the application of this system, the curves being plotted from results published by the manufacturers. It will be noted that although the output demanded from the converter ranged between 30 H.P. minimum and 575 H.P. maximum, the variation in the amount of power absorbed by the induction motor was only between 187 H.P. minimum and 310 H.P. maximum. In the apparatus from which these curves are taken the external resistance in the rotor circuit had a fixed value. A more perfect equaliza-

tion of the input curve is obtained when the value of the external resistance is automatically varied. A modification of the water rheostat equipment to secure this employs a special controlling motor, the current input to which is derived from series transformers intercalated in the stator circuit of the induction motor of the Ilgner set. The action of the controlling motor is so arranged that when

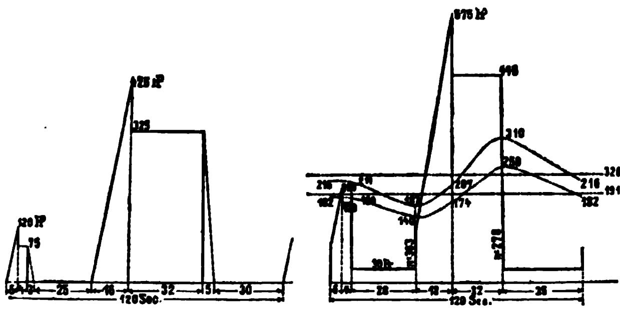


Diagram of the Winding Motor Output. Diagram of the Ilgner Converter Output.

— Output at Shaft of Converter.
—·—·— Output of Three-Phase Motor.
—··—··— Power taken from Three-Phase Supply Mains.

Fig. 70.

the load increases, the rheostat plates are drawn out of the liquid, thus increasing the rotor resistance, increasing the slip, throwing more load on the fly wheel, and thereby relieving the alternating-current supply system of the excess power demand.

Since the equalization of power consumption achieved by this system means that the capacity of the motor element of the Ilgner set may be, and is, proportioned to the average rather than to the maximum demand, the motor

element will always be smaller than the generator element. The ratio of the capacities of the two will depend principally on the nature of the load cycle, the size of generator element as compared with that of the motor element being greatest in a service calling for highly intermittent loads of the maximum fluctuation. This is strikingly illustrated in the case of the installation referred to, in which the motor element is of but 250 H.P., whereas the generator element is proportioned to give a maximum output of 650 kilowatts, or about 870 H.P., the direct-current hoisting motor which it drives having a normal rating of 350 H.P. In other words, an average energy supply of 250 H.P. reinforced by the stored energy of the fly wheel suffices for a duty which would otherwise impose on the supply system peak loads of the amount represented by the maximum output of the generator element. In order to obtain from the rotating masses the amount of energy which these load fluctuations represent, the fly wheel must obviously be of massive construction and worked at high speed, the fly wheel of the converter in question having, for example, a weight of 14,000 pounds and running at a peripheral velocity approaching 150 miles per hour.

CHAPTER V.

INDUCTION MOTORS (Concluded).

Frequency. — Induction motors of frequencies of from 25 to 60 cycles, as constructed at the present time, have somewhat better power factors and efficiencies than higher frequency motors. Motors of a frequency of 125 cycles or thereabouts are seldom built in sizes above 20 H.P. Motors of this frequency being somewhat difficult of construction on account of the small air gap required and the greater number of poles, are not cheaper than 25-cycle or 60-cycle motors of corresponding sizes, as might be expected. The reverse holds good with lower frequencies, 60-cycle motors costing less to build than motors of 25 cycles.

Twenty-five-cycle motors have the disadvantage that on account of difficulties in the winding construction, the speeds are practically limited to 750, 500, 375, and 300 revolutions per minute. The bipolar motor, running at 1500 revolutions, is limited to the smallest sizes. The slow speeds of 300 and 375 revolutions make the motor, unless it be one of great capacity, an expensive piece of apparatus. These conditions limit the average practical speed of 25-cycle motors, of sizes from 5 H.P. to 75 H.P., to 750 revolutions.

Frequencies of 35 to 40 cycles are more desirable for the average conditions of motor work, as they permit a much greater range of commercial speeds.

The frequency of 60 cycles likewise permits the construction of motors with a wide range of speed, and which are comparatively cheap to build throughout the entire list.

Voltage. — Induction motors should not be run at lower voltages than that for which they are designed, as the output varies with the square of the voltage. For instance, if the volts at the motor are 10 per cent lower than normal, a motor which has a maximum output of 30 per cent greater than the full-load output will give only $\left(\frac{90}{100}\right)^2 \times 130 = 105$ per cent of its rated output. This margin is too close for continuous work, as it will not take care of any sudden fluctuation of load or unusual drop in the line. The output of the motor, on a higher voltage circuit than that for which it is designed, will be increased, and the current likewise, especially at light loads. Within ordinary variation of voltages, the power factor and efficiency at full load remain practically unchanged.

In laying out the wiring of a motor which takes a heavy starting current, allowance should be made for this momentary current; otherwise the impressed volts may drop below the point where the motor will start.

Motors with stationary fields could be wound for fairly high voltage, but for the distributed form of winding required to keep down self-induction, the space necessary for high insulation being occupied by the conductor. Standard American motors below 50 H.P. are not wound above 550 volts. It is considered practical to wind larger motors up to 3000 volts or higher. European makers, on the other hand, build motors of 10 H.P. to 30 H.P. for pressures of 500 to 2000 volts, motors of 50 H.P. for 3000 volts, and those of 75 H.P. and larger for 5000 volts,

Power Factor — Efficiency. — It has been seen that the ratio of the energy current of a motor, or the current required in supplying its losses and doing the work to the total current consumed, gives the power factor. The product of the power factor and the actual efficiency of an induction motor gives the apparent efficiency. This last quantity determines the capacity of transformers and generators required for supplying current to the motors. As has been seen, the influence of the power factor extends back in the chain of transmission with greater effect on the supplying circuit, necessitating, in the case of a poor power factor, on account of its inductive effects, an additional increase in the capacity of the transmission lines. For this reason, it is usually of importance that induction motors be designed to give the highest possible power factor. Where the generated power is expensive, it is sometimes of more importance to use motors of higher efficiency than those of high power factor. Under all circumstances, however, it is desirable to have the apparent efficiency of the motors as high as possible.

The power factors of standard commercial induction motors of American manufacture vary at full load from 0.75 to 0.92, depending upon the size and frequency of the motor. The efficiencies range from 0.80 to 0.92. The apparent efficiencies in motors above 5 H.P. output will be found, as a rule, not less than 0.75. This means that the transformer, supplying current to induction motors of average sizes, must have a capacity of 1 kilowatt for every horse power output of the motors.

In quarter-phase motors the windings are in 90 degree relation, and as a rule there is but little latitude for the designer in disposing of the material to the best advan-

tage. In three-phase motors the windings are in 60 degree relationship, and two combinations of winding are usually available, i.e., either the star or delta connection of coils. This circumstance favors the three-phase type somewhat, and with equally good copper arrangement the three-phase type will usually show a slight advantage in power factor, ranging from 1 per cent, where the power factor is about 0.90, to about 3 per cent where the power factor is as low as 0.70, these values being taken at full load.

The following table gives approximate capacities of standard transformers that should be used with two-phase and three-phase induction motors:

H. P. Capacity Motor.	Three-Phase.		Two-Phase.
	2 Transformers.	3 Transformers.	2 Transformers.
1	.6 K.W.	.5 K.W.	.6 K.W.
2	1. "	.75 "	1. "
3	2. "	1. "	1.5 "
5	3. "	2. "	3. "
7½	4. "	2.5 "	4. "
10	5. "	3.5 "	5. "
15	7.5 "	5. "	7.5 "
20	10. "	7.5 "	10. "
30	15. "	10. "	15. "
50	25. "	15. "	25. "
75		25. "	35. "
100		30. "	45. "

The efficiency of commercial induction motors can be somewhat increased by not sparing iron and copper, as the losses of an induction motor are of the same kind as those of a generator, consisting of copper loss, hysteresis and eddy current loss, and friction loss.

The power factor can be bettered by reducing the air

gap and iron density, and thereby lowering the magnetizing or "wattless" current. To do this, however, and retain high efficiency, increases the cost of the motor, and it then becomes a question whether the increased advantages are worth the extra expense. Mechanical considerations limit the clearance between field and armature. Fig. 63 shows the curves of efficiency, power factor, and apparent efficiency, as well as torque and ampere input of a 175-H.P. motor. At full load the efficiency is 91 per cent, the power factor .88, and the apparent efficiency 80 per cent. The efficiency at half load is as good as that at full load; and at one-quarter load the efficiency is still well up, being 85 per cent. The break-down point is at about twice full load. The power factor is highest at about 260 H.P., being over 91 per cent.

In many cases it is desirable to design motors so that their maximum efficiency occurs at about three-quarters load. This is especially desirable for shop work, where the driving motors are called upon intermittently to give full load, the average demand being 15 per cent to 30 per cent less than the load for which they are rated.

Condensers. — Condensers are used to improve the power factor of circuits supplying current to motors by making the motors take current in proportion to the loads. The power factor of the motor itself is not affected, but the wattless lagging current in the motor is offset by the leading current supplied by the condensers, and its pernicious influence confined to the local circuit between the condenser and the motor. Fig. 71 shows the apparent efficiency of a Stanley two-phase motor with and without a condenser.

The condenser consists of numerous thin sheet conduc-

tors, separated by still thinner dielectrics, the whole electrically connected to form two conductors. As the size of the condenser increases rapidly with a low frequency

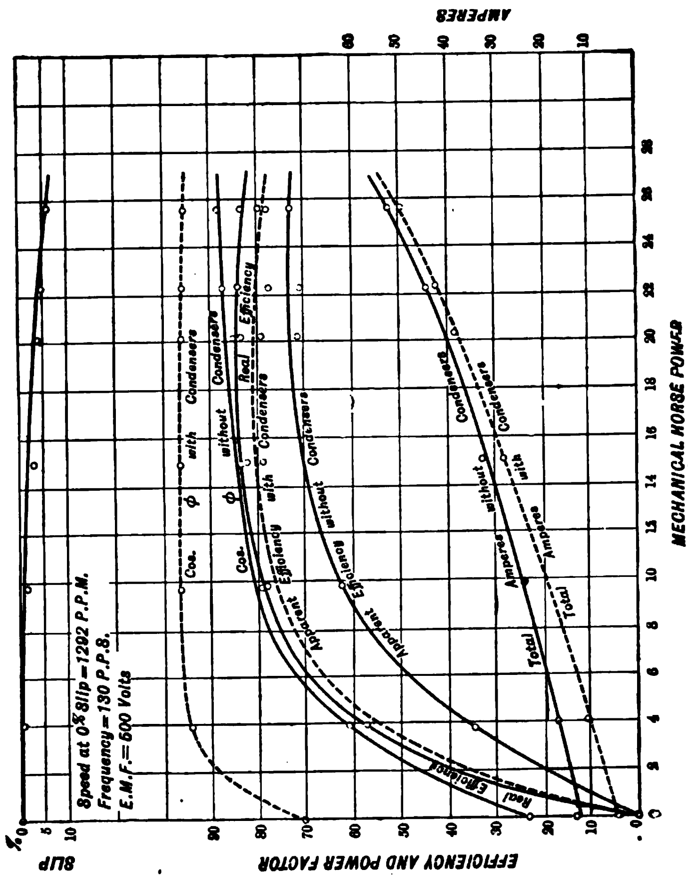


Fig. 71.

and voltage, it is best adapted for circuits of over 100 cycles, and when motors are used for not less than 500-volt circuits.

Single-Phase Motors. — Single-phase induction motors have the characteristic form of polyphase motors. As the flow of energy in the single-phase system is not continuous, as in a polyphase system, their capacity is less than that of polyphase motors of the same dimensions. In respect to torque, power factor and efficiency, the best commercial motors are not so good as polyphase motors. An external starting arrangement, sometimes called a "phase-splitter," is sometimes used with these motors, for artificially producing a torque sufficient to enable them to start from rest under a partial load.

The winding of a two-pole, single-phase motor is shown in Fig. 72. It has a two-phase, interlinked winding, the common terminals being at III. If two currents, having a difference in phase, are introduced, the dead point common to all single-phase motors will be overcome, and the armature will revolve. The displaced phase is produced by a combined resistance and reactance coil, the outline connections of which are shown in Fig. 73. *a* and *b* are the main leads; *c* is a lead to the common terminal of the motor two-phase winding. *R* is a resistance and *L* a choking coil. The current passing through *R* will differ in phase from that flowing through *L*, and the motor will start, when the switch is thrown, with a torque dependent upon the phase difference. The maximum torque will be developed when the currents are 90 degrees apart. This, of course, cannot be obtained with this device. By replacing the resistance by a condenser, a phase difference of 90 degrees or over can be obtained, with a correspondingly increased torque, and a decreased starting current. When the motor reaches speed, the starting coils are cut out, and it then runs as a single-phase motor.

The usual form of motor is provided with a starting device that gives half-load torque at about 150 per cent of full-load current. Full-load torque may be obtained at somewhat over twice full-load current, by a special starting device.

In the single-phase induction motors produced by one of the largest American manufacturers, a special form of automatic clutch pulley is used. With this arrangement

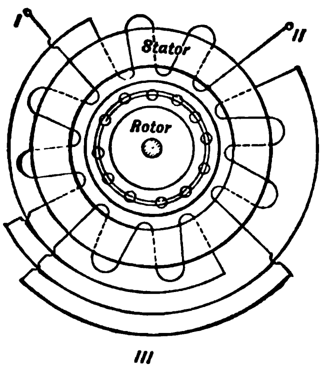


Fig. 72.

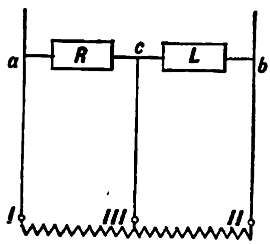


Fig. 73.

the driving power is not applied to the pulley until the armature has reached nearly full speed. Motors of this type give about one and one-half times full-load torque at starting with an input of twice full-load current. The starting device is a combined resistance-reactance, working on the principle already described.

The advantage of the single-phase induction motor over the single-phase synchronous motor lies principally in the fact that the latter motor is liable to be thrown out of step by any fluctuation in the generator speed. The synchronous motor is fairly efficient and can be adjusted to unity

power factor, but the current at starting is very large in proportion to the feeble torque.

A three-phase induction motor will give about 40 per cent of its output when used single-phase. A two-phase motor will give 50 per cent of its two-phase rating under the same conditions. The same motors can be rewound as single-phase motors, and will then have an output of over 75 per cent of their former rating. The unaltered two-phase and three-phase motors can, however, be made to yield, on a single-phase circuit, about 75 per cent of their rating by increasing the voltage 30 per cent above that for which they are wound.

In the single-phase motor manufactured by the Wagner Electric Company the armature contains a definite winding connected to a commutator. In starting, the armature and field are connected as in a repulsion motor, the principles of which are explained in the following section. On attaining full speed a centrifugal device within the armature short circuits the commutator bars and the armature, and the field remains connected across the line. The motor then operates as a simple induction motor. No external starting device is required, there being only two wires from the mains to the motor.

Variable Speed, Single-Phase Motors. — As has been seen, most alternating-current motors are inherently constant speed machines. The synchronous motor is strictly of this description, while the induction motor cannot be made to operate at variable speed without considerable complication or wasteful rheostatic losses.

Motors of the constant speed type are eminently unsuited to certain classes of service, the conditions of railway work being a conspicuous example. While several installations

using the three-phase induction motor for heavy railway service have been made in Europe, American engineers do not consider the induction motor as adapted to the average conditions of railway work. Its speed characteristics result in a poor efficiency of acceleration and in an exaggeration of the station load fluctuations due to grades. With the liberal air gap which mechanical considerations require in a railway motor, the power factor and the apparent efficiency are unsatisfactory. Furthermore, the use of this type of motor requires at least two overhead conductors, a complication which has increased the opposition to any polyphase system for the working circuit.

The appreciation of the obvious advantages to be gained in certain classes of railway work, if the alternating current could be used directly on the trolley line without the necessity of a reconversion into direct current, have, nevertheless, foreshadowed the development of a satisfactory form of alternating-current motor, which should, first, have essentially the speed-torque characteristics of the familiar direct-current series motor, and which should, second, be adapted to single-phase working so as to avoid the complication of more than one overhead conductor. Motors of these characteristics have now been successfully developed, and in a variety of types are already in satisfactory commercial service in this country and in Europe. While differing to some extent in the connections and arrangement of the field circuit, all these types use in common a form of armature not essentially different from that of a direct-current motor, the armature having a commutator of usual form, on which bear two or more sets of brushes.

The types of motor having the desired characteristics and available for possible development are, broadly, the

simple series alternating, the compensated series, the Thomson repulsion, and the compensated repulsion of Winter-Eichberg and of Latour.

In the first of these, which is the simplest in theory, we have the ordinary series motor as used in direct-current practice, with a slight change in the proportions of the strength of the armature and field, the entire magnetic circuit being laminated to reduce the eddy current loss. The connections of this type are shown diagrammatically in Fig. 74, in which *F* and *A* are respectively the field and

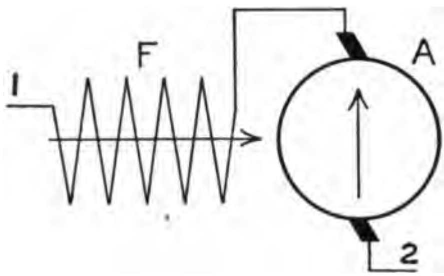


Fig. 74.

armature. The arrows show the direction of the flux generated by the ampere turns on each member. The motor terminals are at 1 and 2, the diagram, like those following, being drawn for a bipolar motor and showing for simplicity but one-half of the field circuit. As is well known, the series motor will operate with alternating current so far as giving torque and speed is concerned, but the alternations of the field flux produce by transformer action a voltage in that coil which is short circuited by the brush during the instant of commutation, and this phenomenon produces bad commutation; also, the alternating flux

due to the current in the armature induces a considerable voltage in the armature, which is a wattless voltage, being the *E.M.F.* of self induction and hence in quadrature with the current. These two characteristics preclude the best results from this type, which is therefore mainly of theoretical interest.

The difference between this motor and the series compensated (Fig. 75) consists in the important addition of

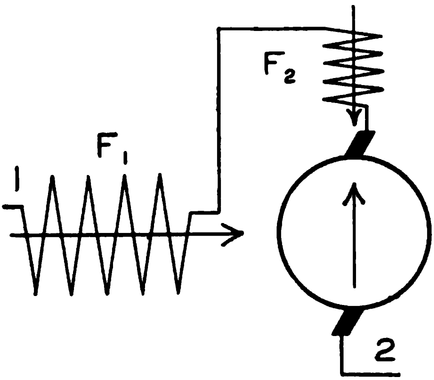


Fig. 75.

an auxiliary field winding, F_2, which produces a magnetomotive force in the same axis as that of the armature reaction but in the opposite direction, as indicated by the arrows. This completely overcomes the effect of the alternating current in the armature so far as concerns the wattless voltage referred to. It also allows the relative armature strength to be greatly increased without inviting the poor commutation which would result in any machine having too great an armature strength. By the use of an armature of this great relative strength it is possible to attain

satisfactory torque with a comparatively weak field, torque being proportional to the product of the field strength and the armature strength. The advantage of this is that the field flux may be made so small that the voltage induced in the short-circuited coil undergoing commutation is reduced to a value which produces no harmful effects on commutation. This machine has all the characteristics of the direct-current series motor, i.e., a very large torque at starting, and a decreasing torque with increasing speed, with the possibility of operating at any speed which is allowed by the mechanical construction of the machine.

This motor takes its name from the effect produced by the auxiliary field winding referred to, which compensates for the armature reaction. The compensating winding is embedded in slots cut in the faces of the main field poles, and so arranged that the direction of the current in the compensating winding at any instant is opposite to the direction of the flow of current in the armature conductors lying directly beneath it.

In the repulsion motor, Fig. 76, the field has a distributed winding similar to that of an induction motor primary. The field and armature circuits are not electrically connected, the current in the armature being that induced by the stator or field acting like the primary of a transformer. The two sets of brushes as shown are connected to each other by a conductor of negligible resistance, and the brushes are given a slight shift in the direction of rotation. It is in fact this shifting of the brushes that produces rotation, and the direction of rotation depends on the direction of brush shift. Thus the armature, short circuited through the low resistance lead which joins the opposite brushes, plays the part of the short-circuited secondary coil of a

transformer, but with this difference, viz., that the axis of the flux produced by the armature ampere turns takes up a direction in space parallel to the diameter which joins the brushes, whatever may be the angle which this makes with the axis of the field flux.

If the brushes are set on a diameter parallel with the field flux as at *xy*, a consideration of the transformer action taking place will show that maximum *E.M.F.* is induced since each set of brushes is in effect the terminal of a secondary of many turns, all of which are in series and which cut the flux in such a way that the *E.M.F* generated

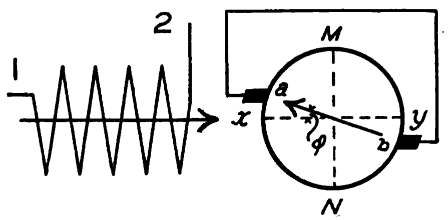


Fig. 76.

in all the turns is additive. Maximum current will therefore flow through the armature windings, since the terminals are short circuited on each other. Considering the armature to be equally divided by the vertical line *MN*, it is apparent that with the brushes at *xy* the ampere turns produced by the section *Mx* are equal and opposite to those produced by the section *Nx*. A similar condition prevails in respect to *My* and *Ny*. Hence a condition of no torque results, the only effect of the induced armature current being a force parallel to the line of the field flux, like the repelling action existing between primary and secondary coils in an ordinary transformer. To produce torque *Mx*

must be unequal to Nx, — in other words there must be some resultant flow of current from M around to N or vice versa, a condition which does not exist under the conditions assumed.

Let the brushes now be considered as placed on the diameter MN perpendicular to the axis of field flux. Since the direction of field flux is such as to produce maximum armature *E.M.F.* between the points xy, the difference of potential between M and N is zero, and no current will flow in the armature windings.

We have, therefore, the two extreme positions in which the brushes may be placed. In the first we have maximum armature current but no torque, and in the second, zero armature current and also zero torque. Since all the current flowing in the armature is an induced current, requiring that some *E.M.F.* shall exist between the short-circuited brushes, it follows, first, that the brushes shall be set at some point away from MN so that an *E.M.F.* may be set up, and, second, that they shall be set at some point away from xy so that the current thus induced shall have a resultant value in the direction MN so as to produce torque. Since the amount of current that flows in the armature varies with the amount by which the brushes are angularly displaced from MN, and since the proportion of this induced current that is effective in producing torque varies with the angular displacement from xy, there will be some intermediate position corresponding to maximum torque. In the average motor this position is along the diameter ab where the angle ϕ is about 15 degrees. By altering the angle ϕ it will be seen that the torque for a given speed may be raised or lowered at will. This machine has the same characteristics as the compensated series

motor as to decrease of torque with increase of speed, and at the instant of starting its performance is identical with that of the compensated series machine. At a speed near synchronism the resultant field due to the flux set up by the primary and that due to the flux produced by the armature current takes on the character of the revolving field of a polyphase motor, and there is thus no pulsation of flux through the coil that is spanned by the brush during the instant of commutation. Near synchronism, therefore, the commutation is better than in the series or the compensated series type; but as the speed increases above this point the field loses its rotary character and the field due to primary flux predominates. This causes a considerable voltage to be generated by rotation in the coil undergoing commutation, which produces bad commutation as the speed increases, so that the practical limit of speed is somewhere below one and one-half times synchronous speed. Thus in a four-pole, 25 cycle motor very good commutation would be expected at 750 revolutions, but the maximum tolerable speed would be limited to about 1000 revolutions.

It has been seen that in the repulsion motor the action taking place in the armature is that due to the two components acting at right angles to each other into which the induced armature current may be considered as resolved. Instead of effecting this resolution by means of brush shift it is apparent that the equivalent result may be produced by introducing into the armature two separate currents at right angles, selecting for each such a value that their resultant shall produce an effect similar to the single current which exists in the armature of the repulsion motor. With proper relative values for these two separate currents it will be seen that their resultant can be made to act along an

axis which makes an angle ϕ of 15 degrees with that of the field flux, and that a variation in the relative strengths of the two currents will effect any desired change in the magnitude of the angle ϕ. On this principle are devised the so-called compensated repulsion motors of Winter-Eichberg and of Latour, which are similar to each other in theory, but different slightly in the brush arrangement. It will therefore be sufficient to describe the Winter-Eichberg type, of which the connections are given in Fig. 77.

The current from the primary or stator is led into the rotor by the brushes bb' at right angles to the axis of main

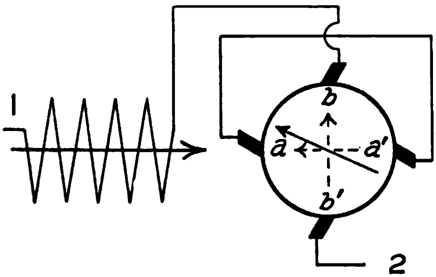


Fig. 77.

action aa'. It is this current which generates the torque-producing field, the main stator winding being regarded merely as the primary of a transformer which induces secondary currents in the armature in the direction $a'a$. The resultant of the two actions along the diameters $b'b$ and $a'a$ is effective in the direction of the full-line arrow within the circle. The angle of resultant action may be varied by changing the relative magnitude of the component actions as explained. This is effected in practice by supplying the circuit bb' from the secondary of a current transformer, not shown, instead of passing the main current

directly into bb'. Taps in the secondary winding of the current transformer permit any desired value to be given to the component bb', a regulation being thus secured which is similar to that ensuing when a change is made in the angle of brush shift in the plain repulsion motor.

Motors of all these types operate best on circuits of low frequency, and in most installations the current supply is at 25 cycles. For very large motors the use of still lower

Fig. 78.

frequency makes it easier to secure a good design, and it has in some cases been proposed to go as low as 12.5 cycles. In fact the lower the frequency the better will be the possible performance and the less the cost of a motor of given capacity, a condition which reaches its obvious limit with a current supply at zero frequency, in other words, with direct current. To secure satisfactory commutation, motors like the plain series or the series compensated, in which the

main current passes directly into the armature, are best designed for a low potential not exceeding, say, 300 volts. In the repulsion and the Winter-Eichberg types where the field circuit is not in electrical connection with the armature it is theoretically possible to wind the stator for very high potentials and thus, in the case of a high voltage trolley, dispense with the step-down transformer which with the other types of motor must be carried on the car. Experience has demonstrated, however, that a high voltage winding,

Fig. 79.

even in the stationary element, cannot safely be employed in a machine like a railway motor, which must be of the most rugged construction and necessarily subject to less care than can be given to a stationary motor, and in which, finally, the space at the designer's disposal is strictly limited by considerations of track gauge, wheel base, and wheel diameter. For this reason these types are now designed for about 750 volts as a maximum.

The general appearance of the field structure of all these motors is illustrated in Fig. 78, which shows the

cylindrical laminated body carrying the field winding which is embedded in slots cut in the interior of the ring. The general mechanical design follows the lines established by direct-current practice, as will be seen from Fig. 79, showing a completed motor housed in its supporting and enclosing frame.

CHAPTER VI.

SYNCHRONOUS MOTORS.

General. — Any alternating-current generator, with little or no change, can be used as a synchronous motor. Electrically and mechanically the motor resembles the corresponding generator, and must be provided with the same station equipment, including some source of exciting current. The synchronous motor, especially in units of large output, possesses a number of features which makes its use at times preferable to that of the induction motor. Besides the advantage of an unvarying speed at all loads, the power factor can be altered at will by changing the exciting current and made equal to unity at any load. The current can even be made leading, to offset a lagging current in other parts of the system. The synchronous motor, especially at low speeds, is cheaper to build than the induction motor, and its efficiency, as a rule, will be found to be higher.

As a partial offset to these advantages, the synchronous motor is not adapted for use where a large starting torque or frequent starting of the load is necessary. It does not admit of independent speed regulation. It also has the disadvantage of requiring certain station appliances and an exciting current. Another objection to the synchronous motor is its tendency to hunt unless the conditions of operation are properly chosen.

Speed. — The speed of the synchronous motor is not necessarily the generator speed, but a speed which, multiplied by the number of poles, gives a product equal to the generator alternations. A motor, with twice as many poles as the generator, will have half its speed, or vice versa. As load is thrown on the synchronous motor, there is a lag in the relative positions of armature winding and pole face, corresponding to a change in phase displacement between the impressed and the counter *E.M.F.* The effective counter *E.M.F.* is thereby reduced, which permits a larger flow of current.

The motor speed is independent of the voltage and cannot be altered except by changing the generator speed. It is important, therefore, that the regulation of the prime mover be as perfect as possible, both in the number of revolutions per minute and in the angular speed; otherwise, as the fly-wheel capacity of the motor is sufficient to absorb considerable energy, it tends to run at constant speed, and if the source of power is pulsating, heavy fluctuating currents are set up between the motor and generator, reducing the motor capacity and producing voltage fluctuations which may be prohibitive.

Torque and Output. — A synchronous motor at starting acts somewhat as an induction motor. Consequently, any variation of its proportions, such as the shape of the pole pieces, armature reaction, and nature of the winding — i.e., distributed or unitooth — affects its starting torque. The starting torque may vary from nothing to 20 or 30 per cent of full-load running torque, depending upon the motor design. When once in motion, the motor will rapidly attain synchronous speed. After synchronism is attained, polyphase motors, as usually constructed, will

carry four to five times full load unless the applied potential is allowed to fall below normal. If further loaded, they fall out of synchronism, and must be started afresh. Single-phase synchronous motors have dead points, and will not start from rest, some extraneous source of power being necessary to start and to bring up to speed motors of this type. This is usually effected by an induction motor. In some cases where a direct-current source of power is available the direct-connected (or belted) exciter may be used as a starting motor, although the exciter, unless specially proportioned for use in this way, will usually be of insufficient capacity. The starting effort necessary to bring a synchronous motor up to speed may be large, sometimes as great as 20 per cent of the rated full-load torque of the motor, and this maximum condition is usually beyond the torque that can be delivered by the exciter, whose rating is seldom higher than five per cent of the motor rating.

The limit to the torque and output of a synchronous motor is dependent mainly upon the terminal voltage. Under rated voltage the margin of most motors, before the break-down point is reached, is sufficient to enable them to stand a heavy overload. Variation of the speed of the prime mover will reduce the maximum output.

Voltage. — The relation of impressed volts to the maximum output is the same in synchronous as in induction motors, the output and the starting torque varying within certain limits as the square of the volts. It is essential, therefore, that the pressure be kept at the rated voltage of the motor; otherwise the motor may not start at all, particularly if it consumes an excessive starting current.

Synchronous motors may be wound for a voltage as high as that of alternating-current generators of equal

capacity and like construction. Motors of the revolving armature type are not therefore well adapted to very high potentials, and have been almost completely superseded by the revolving field type by reason of the same advantages as are secured thereby in the construction of generators. A further advantage is that motors of the revolving field type as ordinarily proportioned have a somewhat greater starting torque than those of the revolving armature type on account of the greater arc covered by the pole face. Motors of 100 kilowatts to 500 kilowatts are frequently wound for potentials as high as 6000 volts; larger motors are frequently designed for 12,000 or 13,000 volts, and these limits can be exceeded by several thousand volts if occasion demands, although, as in the case of generators, it is usually found more convenient and less costly to interpose transformers than to design the windings for potentials much in excess of about 13,000 volts.

Methods of Starting. — When a large torque is required to turn over the load, as in the case of mill machinery or long lines of shafting and belting, a friction clutch must be used. This permits the load to be gradually thrown on the motor after it reaches synchronism. The clutch may be mounted on the motor base extended, an extra standard being required for this purpose; or the motor may be belted to a line shaft on which there is a coupling. This is the cheaper and more usual method. Fig. 80 shows a 300-H.P. motor, built with extended base, carrying a clutch and driving pulley. In selecting a coupling for this class of work, one of ample proportions should be used, as it must start the load gradually, without exceeding the breakdown point of the motor, and without overheating.

The operations in starting a synchronous motor are

Fig. 80

about as follows: First, the main switch is closed and the motor with its fields unexcited will start with a small torque due to the induced currents in the pole pieces, and gradually acquire speed. When maximum speed is attained, — and this may be something less than synchronous speed, — the current from the exciter can be switched into the fields, the exciter commonly being direct-connected to or belt-driven by the motor, or in the case of a single station containing several synchronous motors, being driven from a separate source of power and of sufficient capacity to excite all motors simultaneously. At the moment considered, when the motor has nearly reached synchronous speed, the angular velocity of the field structure (considering the stationary armature type of machine) is nearly equal to that of the rotating induced field engendered by the armature current, so that as soon as the field winding is excited the rotating structure will accelerate sharply and "lock into step." The full load can then safely be thrown on the motor by the friction clutch, if one is used.

With full voltage impressed the current taken at starting may be anything from 150 per cent of full-load current to several times normal current, being limited by the resistance and self-induction of the armature winding, i.e., its impedance. This excessive starting current, as it is of an inductive character, may cause a large drop in the line, and disarrange the voltage of the entire system.

If the motor takes a large proportion of the generator output, or is used in connection with lights, and started and stopped at frequent intervals, some means should be employed to reduce the current. This can be done, as in the case of the induction motor, by the use of a resistance,

a reactance, or a compensator in the main circuit, or by a small starting motor. A compensator starter is often used. This may be of substantially the type illustrated for use with induction motors (see Figs. 56 and 57) or may be of rather more elaborate construction with a large number of steps like that shown in Fig. 81.

With 50 per cent of the impressed volts, the synchronous motor, when properly proportioned, will take, at starting,

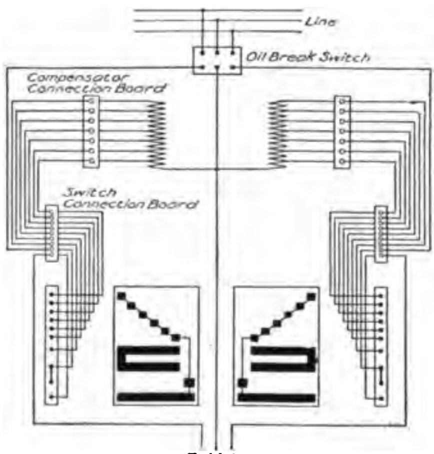


Fig. 81.

a current from the line equal to about full-load current, and start with a torque about 15 per cent of the full-load running torque. Where the magnitude of the starting current is of no consideration and the highest possible starting torque is essential, the compensator may be designed to raise instead of to lower the line potential. In this way with a properly designed motor, a starting effort equal to two-thirds normal full-load torque may be produced.

This, however, represents an unusual condition, and such arrangements are adopted only in rare instances.

A starting motor, of the induction type, is the best means of reducing the current at starting. The current taken by this small motor cannot seriously affect the voltage of the circuit. This method should be employed when the motor is started frequently, or when a low starting current is essential to preserve good regulation. Where no load is connected to the motor at the time of starting, a starting motor having a nominal rating of about one-eighth the capacity of the synchronous motor will usually be found of sufficient size to meet all average conditions. Such a motor should be capable of a maximum torque equal to about double its own rating, or, say, equal to one-quarter of the normal full-load torque of the synchronous motor. The continuous output rating of a starting motor is a matter of small consequence, the only factor of importance being its ability to deliver high torque for the short period of time necessary in getting up to speed. With a well-designed starting motor, proportioned to give a maximum torque per unit of current input, synchronous motors without load can be started with a current from the line not exceeding about one-third their normal full-load rating. Such starting motors, to secure good torque, have high resistance armatures and hence large slip. When direct-connected they are designed with a fewer number of poles than the synchronous motor, so that their synchronous speed minus the slip, in other words, their free running speed, shall be such as to drive the synchronous motor at a speed slightly in excess of normal. The equivalent result where the starting motor is geared is secured by choosing a suitable gear ratio. In

this way when the attained speed of the motor is brought above normal, current is cut off from the induction motor and the synchronous motor is switched in at the moment synchronism is reached during the gradual fall in speed that follows the removal of the driving power. Where the maximum speed is only slightly in excess of the normal, a fine adjustment is possible by somewhat increasing the excitation of the synchronous motor. This increases the core loss of the synchronous motor and thus the power required to drive it, and the high-slip induction motor responding sensitively in speed change to variation of load will drop to a speed at which the necessary synchronizing may be effected.

Where the synchronous motor has a small number of poles it may be difficult to design a direct-connected starting motor with enough slip to bring its free running speed down to that of the synchronous motor. In such cases a resistance intercalated in the circuit supplying the starting motor, this resistance being connected in after full speed is reached, will produce the desired result, whereupon synchronizing may be effected in the manner just described.

Synchronizing of motors with each other or with the supply system is effected in precisely the same manner as in the case of generators. As in the case of induction motors, reversal of the direction of rotation is secured by reversal of any two leads in a three-phase motor and by reversing the leads of either phase in a two-phase motor.

Fig. 82 shows a 600-H.P. 50-cycle three-phase motor with direct-connected induction motor starter. The synchronous motor has 30 poles and operates at 200 revolutions per minute. The induction starter has 24 poles and is given a nominal rating of 75 H.P.

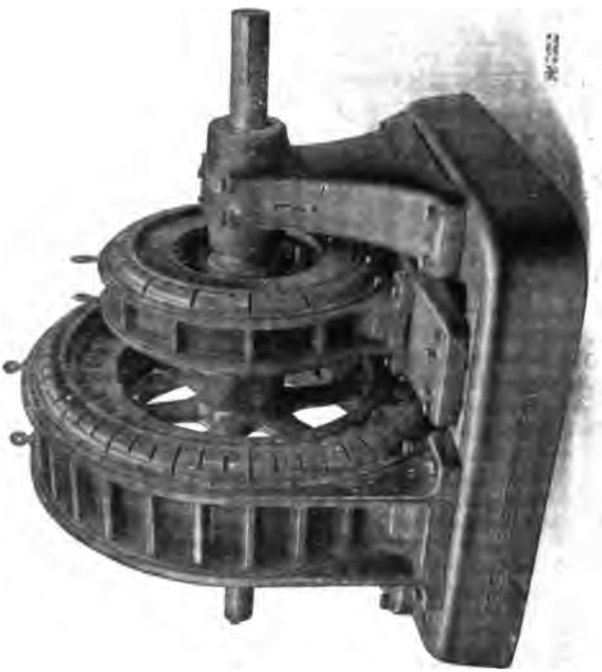


Fig. 82.

Fig. 83 shows a 225-H.P. motor with geared starting motor. The lever shown at the left slides the motor pinion out of contact with the large gear wheel as soon as the synchronous motor has been switched on the line. This motor is direct-connected to an air compressor at a mining plant in Mexico.

Many forms of self-starting synchronous motors have been devised for use on single-phase circuits. Most of these are provided with a commutator for self-excitation, and a starting device. A commutator, in series with the field winding, rectifies the current at the instant the main armature current is in phase for producing a slight torque. When the motor reaches speed, the commutator is cut out. One of these types is the single-phase motor made by the Fort Wayne Company, which embodies a modification of this construction. The main current is first thrown on a continuous-current winding connected to a commutator, and laid over the alternating-current winding on the armature, which is connected to collector rings. When the motor reaches synchronism, the main current is switched into the alternating-current winding, and the field circuit closed on the starting winding through the commutator.

When a synchronous motor is started by the application of voltage to its armature terminals, the armature winding plays the part of a transformer primary with respect to the field winding, which latter acts as the secondary. If the ratio of field turns to armature turns is large, high voltages may consequently be induced in the field circuit. These are reduced as far as possible by using a minimum number of turns in the field, designing it, in other words, for a moderate excitation potential, as low as 50 volts in extreme cases. In the revolving field type, where the use of

Fig. 83.

strip copper for the exciting winding gives a small number of turns and makes it easy to insulate the coil thoroughly, these induced potentials are kept within moderate limits so that no danger to the machine results. The voltages generated in this way, nevertheless, are frequently high enough to give a dangerous shock, and operators are therefore careful to avoid contact with any part of the field circuit during starting.

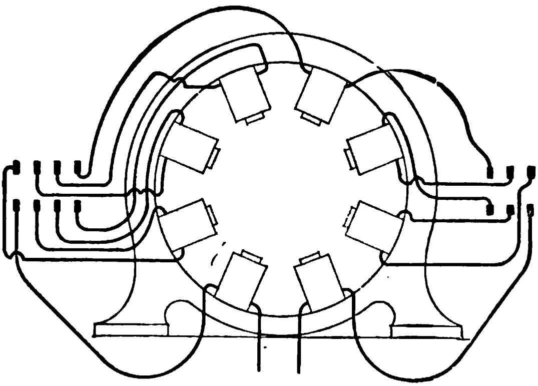


Fig. 84.

In the case of stationary field machines, including rotary converters, it is customary to cut down the magnitude of the induced potential by breaking up the fields into a number of parts, or by open-circuiting each field spool, as shown in Fig. 84. Leads from each spool are brought out to convenient switches on the motor frame. The motor is started with these open. When synchronism is reached the switches are closed, thus putting the field coils in series, and throwing them in circuit with the exciter.

Where a synchronous motor is so connected as to take the entire output of a generator, it is possible to start both

motor and generator from rest simultaneously. The procedure is then as follows. All switches between the two are closed, and the generator, strongly excited, is slowly revolved. The motor, with its field circuit not yet excited, now starts up, revolving at a speed corresponding to the low frequency which is being supplied to it.

As soon as the motor is well in motion it is given full excitation and locks into step with the generator. The speed of the latter is gradually increased, the speed of the motor accelerating simultaneously, till at last full speed is reached and normal conditions of operation attained.

Motors with "Amortisseur" Winding. — Synchronous motors are frequently equipped with an auxiliary winding consisting of brass or copper bars imbedded in the pole face and having their ends connected by short-circuiting rings. Such an arrangement is termed an "amortisseur" winding, and amounts in effect to superposing on the field structure a winding analogous to that of the armature of a squirrel-cage, or short-circuited, type induction motor. At the moment of starting, therefore, a synchronous motor so equipped has the characteristics of a squirrel-cage induction motor with high resistance, short-circuited secondary, with the result that the starting torque is much higher than in synchronous motors of the ordinary form. By this arrangement it is in most cases easy to secure, with one and one-half times full-load current in the line, a starting torque equivalent to one-third of the full-load running torque. The regulation of the motor, that is, its sensitiveness in respect to change of power factor with change of load, is also improved by reason of the compensating action which the squirrel-cage winding provides. A motor of this type, with constant field excitation, will therefore

maintain a more nearly constant power factor with changes of load or changes in the line conditions. The action of the squirrel-cage winding in this respect, and with reference to the improved stability or freedom from hunting which it gives, is similar to, but more effective than, that achieved by the use of metal bridges between the pole tips (such as are illustrated in Fig. 21). Eddy currents of greater or less magnitude always exist in such metal bridges, and as these eddy-current losses are less in the squirrel-cage structure, the efficiency of the motor is correspondingly better. Motors of this type are thus seen to possess, particularly in respect to starting, certain characteristics of an induction motor, and are therefore sometimes referred to as "synchronous induction motors."

Field Excitation. — Since the synchronous motor runs at constant speed, an increase in the field excitation will cause a corresponding increase in the counter *E.M.F.* generated in the motor. If the field excitation is sufficiently increased, this counter *E.M.F.* would thus be made considerably greater than the *E.M.F.* impressed at the motor terminals. Since the counter *E.M.F.* must always assume such a value with relation to the impressed *E.M.F.* as will permit to flow into the motor that particular value of current corresponding to the load, and, further, since the adjustment of counter *E.M.F.* necessary to fulfill this condition cannot be effected by automatic change of speed (as in the case of a direct-current motor), the only way in which the counter *E.M.F.* can alter will be by a change in the flux which produces it. This, in a synchronous motor over-excited in the way assumed, is brought about by change of phase of the current with respect to the *E.M.F.* The current will therefore advance in phase ahead of the

E.M.F., since in this way, by armature reaction, the flux in the armature generated by the leading current will be directly opposed to the flux generated by the field winding. The amount of lead will be such that the net flux, that is, the difference between the flux produced by the field and the opposing flux generated by the leading current in the armature, is brought to a value which will produce a counter *E.M.F.* proportionate to the load. Conversely, if a weak field excitation is applied, a lagging current will be taken, the armature flux produced by it being additive to that generated in the field poles.

It follows then that by simply changing the strength of the exciting current, the armature current for any condition of load of the synchronous motor can be made lagging or leading with respect to the impressed *E.M.F.* or in phase with it. In other words, the current input to the motor depends upon the field excitation, although the amount of energy consumed at a given load remains unchanged except so far as it is affected by minor variations in the efficiency under the different conditions of operation.

The effect upon the armature current produced by varying the field excitation is shown by the curves in Fig. 85. The values at the left of the diagram are those corresponding to a low excitation, and the armature current is lagging. With increase of excitation, the angle of lag and the current input diminish until a minimum current input is reached, at which the current is in phase with the *E.M.F.* A further increase in excitation increases the current input, which is now leading with respect to the *E.M.F.*, the angle of lead and the current input continuing to increase as the excitation is increased until saturation of the magnetic circuit is reached.

There is, therefore, one value of the exciting current for any given load for which the armature current is a minimum, and at which the motor will be operating at unity power factor. In motors of good regulation, this value varies but slightly with different loads, a fact which is especially noticeable, for the reasons already suggested, in the case of motors equipped with squirrel-cage winding. The term "phase characteristic" is given to the curves

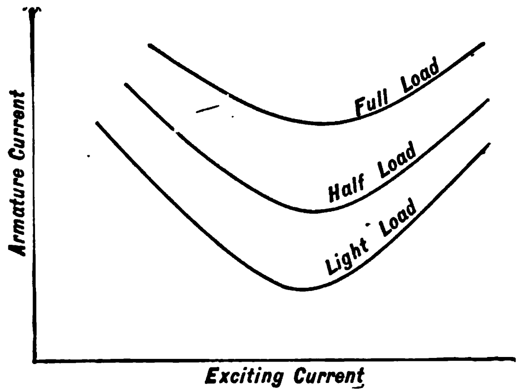


Fig. 85.

showing the change of armature current with variation of field excitation. They are sometimes referred to also as Mordey's "V curves," from the name of the English engineer who was the first to determine the existence and nature of the phenomenon.

The result obtained from this property of the synchronous motor, of producing at will any displacement of phase between current and *E.M.F.*, is the possibility of annulling the reactance due to the inductance of the line, and at the same time of compensating for a certain amount of lagging

current due to inductive loads in other parts of the circuit. When over-excited, the synchronous motor acts like a great condenser. It will take care of a total current made up of energy and wattless components, to an extent equal to its rated ampere output.

Synchronous motors which are used primarily to produce leading current for the purposes indicated, are frequently called "rotary condensers." When used for this purpose they may be run light or made to convert a cer-

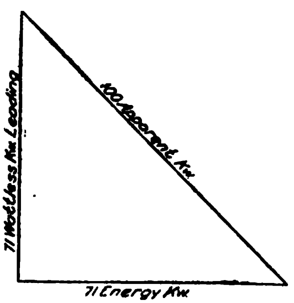


Fig. 86.

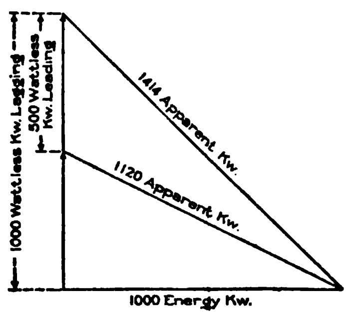


Fig. 87.

tain proportion of the current input into useful mechanical work. This proportion, that is, the energy component of the current input, may be made to bear any desired relation to the leading wattless component. If the mechanical load is sufficient, the electrical and magnetic material in the synchronous motor is used to the best advantage when the arithmetic sum of the leading and energy components is a maximum. This condition, when the field is adjusted to give 71 per cent power factor leading, is shown in the diagram (Fig. 86). Assuming that a system has an inductive (lagging) load of 1414 apparent kilowatts at

71 per cent power factor, that is, 1000 actual kilowatts, it is evident from the diagram shown in Fig. 87 that adding 500 wattless kilowatts of leading current will reduce the load to 1120 apparent kilowatts, or 89 per cent power factor. In this case 294 (1414 minus 1120) apparent kilowatts are gained. It will be noted, however, that a further addition of 500 wattless kilowatts of leading current to the system at the higher power factor of 89 per cent would save only 120 (1120 minus 1000) apparent kilowatts, showing the greater proportionate improvement secured by a given amount of leading current when the power factor of the entire system is low.

Synchronous motors of the polyphase type are separately excited. No series winding or automatic compounding is required.

When generators provided with compound winding are used as synchronous motors, it will be found that increased separate excitation is required, since the series fields are necessarily omitted in the motor. The standard exciters usually furnished with generators of this type under 250 kilowatt capacity must, as a rule, be replaced by the next larger sizes. The following table gives the average exciting current required by standard compound wound polyphase generators and synchronous motors of moderate output, power factor being taken as unity. The exciter capacities given are sufficient to take care of inductive conditions. The exciters should have ample capacity, as they are a vital part of the system, and should not be taxed to their full capacity. In a station where several synchronous motors or generators are used, it is customary to install two independently driven exciting dynamos, each one of which has capacity to furnish sufficient excitation for all machines.

Exciting Current and Exciters for Standard Polyphase Generators and Synchronous Motors.

Generator or Motor. Rating K. W.		25–60 Cycles.		Exciter Capacity.
		Separate Exciting Current.	Voltage.	
50–	Generator	6	125	1½ K.W.
	Motor	10	125	2 K.W. to 2½ K.W.
75–	Generator	8	125	2 K.W. to 2½ K.W.
	Motor	13	125	2½ K.W.
100–	Generator	10	125	2½ K.W.
	Motor	15	125	2½ K.W.
150–	Generator	12	125	2½ K.W.
	Motor	20	125	3½ K.W. to 4½ K.W.
250–	Generator	19	125	4½ K.W.
	Motor	32	125	7½ K.W.

Power Factor. — The maximum efficiency of the motor and circuit exists when the current and *E.M.F.* supplied to the motor are in phase — i.e., when the power factor is unity. This is also a condition of minimum current, and the drop in the line is that due to ohmic resistance only. When the current is in advance of, or lagging behind, the impressed volts, the power factor is less than unity. It is possible, as we have seen, so to adjust the exciting current of a synchronous motor, that its power factor may be unity at any load. In this way a low power factor of the supplying circuit, due to induction motors, may be raised any amount.

On account of armature reaction, a motor which has its excitation adjusted to give a power factor of unity at full load, will take at all points below full load, a leading current, and have a power factor less than 100 per cent.

For the average case, it will be found most desirable so to excite the motor fields that the minimum current and highest power factor are reached at about average load. The power factor will be leading at lighter, and lagging at greater, loads. Except in the case of synchronous motors of abnormally bad design, the power factor, with properly excited fields, will have a high value over a wide range of load. Even motors with considerable armature reaction will have only a slightly drooping curve of power factor.

Motors which, as generators, would have excellent inherent regulation — i.e., small armature reaction and self-induction — can be made to have, with one adjustment of the field, practically 100 per cent power factor at all but light loads. The advantage of a more uniform power factor in such motors is offset by their instability during voltage fluctuations. Some self-induction is desirable in order to prevent exchange of current between motor and lines when the impressed volts vary, as often happens in power transmissions. In selecting a synchronous motor, therefore, preference should be given to that one which, as a generator, would not have very close inherent regulation. Machines of not such good regulation, have, as a rule, a higher efficiency, and take less starting current.

To predetermine the proper field strength which will give the maximum condition of efficiency, it is necessary to know the conditions of the system, — the reactance of the generator and line, the average load and its power factor, and the characteristics of the motor. Each case is a problem by itself, and must be judged by the special conditions affecting it.

A synchronous motor will take no more than its rated amperes without overheating, whatever the phase relation

of current and *E.M.F.* may be. If the inductive load at the receiving end is large as compared with the capacity of the motor, the synchronous motor may be unable to raise the power factor of the system appreciably while driving its own load.

It will be found that, for every load and every power

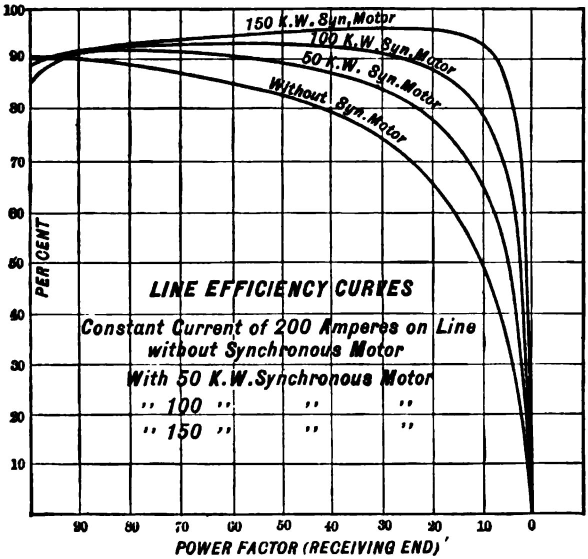


Fig. 88.

factor, there is a synchronous motor capacity which will make the efficiency of the system a maximum. Mr. E. J. Berg has calculated the influence of synchronous motors upon the efficiency of alternating systems. Fig. 88 shows the different efficiencies of a transmission of a constant current of 200 amperes when a synchronous motor of 50, 100, or 150 kilowatts is running as a compensator at the

receiving end, which is assumed to have varying power factors. The circuit is supposed to have the following constants:

Current	= 200 amperes.
Resistance	= 0.52 ohm.
Reactance	= 1.45 ohms.
Voltage at motor	= 1000.

It will be noticed that, as the power factor diminishes at the receiving end, the line efficiency is increased by using the larger synchronous motors — i.e., will transmit a greater amount of energy for the same loss. The line efficiency is greatest when using the 150-kilowatt motor at all power factors below 87. The line efficiency is improved by entirely dispensing with the motors when the power factor is greater than 95. The leading current of the motors is then in excess of the lagging current of the receiving circuit, thereby increasing the total current, or when maintaining a constant current, as in the present case, decreasing the energy current — i.e., the amount of power that can be transmitted over the lines with the conditions as given.

Instability. — When a number of synchronous motors are running at the end of a long transmission line, it is sometimes found that a condition of instability exists, especially during load variations. This is shown by an interchange of synchronizing current. This difficulty may in part be overcome by under-exciting the motor fields, which gives a lagging armature current.

The instability or "hunting" of synchronous motors may also be caused by the periodic variation in the angular velocity of the prime mover. The permissible limits of angular variation have been fixed principally because of the effect on the operation of synchronous apparatus of

changes in frequency of the supply current during each revolution of the generator. Any disturbance distorting the motor-field flux, thereby pulling ahead or retarding the revolving element, will increase the tendency to hunt. This tendency is more noticeable in motors of high voltage when designed with armatures having few slots. It may be reduced by various forms of anti-hunting devices, such as copper rings surrounding the poles, by heavy metal bridges between the poles, or, better still, by the amortisseur winding previously described.

CHAPTER VII.

TRANSFORMERS.

TRANSFORMERS for use on polyphase circuits may be either ordinary single-phase transformers suitably grouped, or may be of a distinct type wound polyphase. Polyphase transformers usually have as many magnetic circuits as there are phases, although the two-phase transformer is sometimes made with three magnetic circuits connected on the three-wire, two-phase system. In the polyphase transformer, since the flux is not a maximum in all phases at the same time, the iron is used to better advantage than in separate single-phase transformers and less is required for the same output.

Until quite recently the polyphase transformer has had only limited use in this country, American engineers for the most part having favored an appropriate combination of single-phase transformers for all the commercial polyphase systems. This preference for the single-phase transformer has been based largely on the simple construction and greater flexibility of the single-phase type, especially because in the three-phase system damage to one transformer does not interrupt the continuity of polyphase transformation, so that with three transformers normally in service practically two-thirds of the load can be carried by two of the transformers in the event of damage to the third. A three-phase transformer can, with proper construction, be made

nearly as convenient in this respect as the single-phase combination by cutting out the damaged phase in the event of injury. The advantage of three-phase transformers in the matter of smaller floor space and lower cost are now causing them to be viewed with greater favor than formerly, and they are being used in increasing numbers. The saving in cost amounts usually to more than 10 per cent, and the floor space may be less than three-quarters of that required for an equal output in the single-phase type.

The increasing size of electrical units required by modern conditions has demanded the construction of very large transformer units in both three-phase and single-phase types, and in these certain features of construction not found in the smaller units are embodied. These relate primarily to the methods for getting rid of the heat generated in the core and windings. In small transformers the heat can be readily dissipated by natural radiation from the exterior of the transformer casing. The radiating surface of a transformer increases as the square of its linear dimensions, while its mass, which increases directly with the output, varies as the cube of the dimensions. For this reason the increase of radiating surface does not keep pace with the increase of output, and a capacity is soon reached where artificial means must be resorted to for the dissipation of the heat.

The ordinary transformer of moderate capacity is cooled by being immersed in oil. The heat generated in the coils and iron, taken up by the oil, is transmitted to the iron casing and is thence dissipated by radiation. Transformers of this type are rarely built of larger size than 100 to 150 kilowatts. When higher capacities than these are reached either the radiating surface must be made very large, requir-

ing a large tank and a great quantity of oil, or by a liberal use of copper and iron the transformer losses must be made very low, or a combination of these expedients must be adopted, resulting, under either alternative, in a rapid increase in cost. Transformers of large capacity must accordingly have some special means of getting rid of the

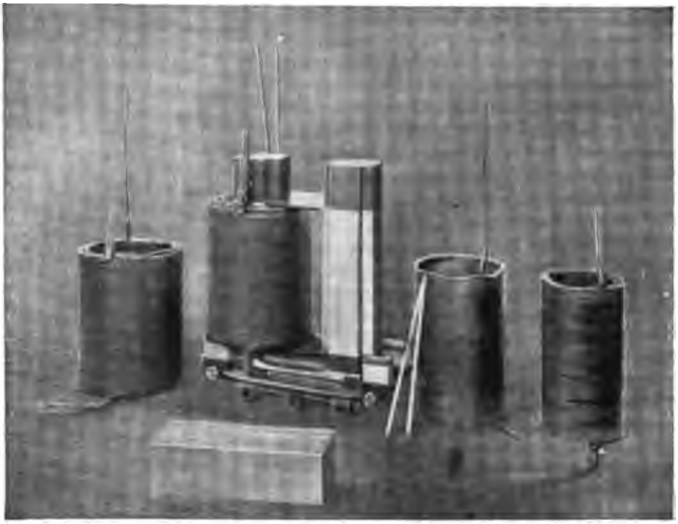


Fig. 89.

heat generated within them. A number of methods of cooling are employed, but all transformers may be classed as belonging either to the self-cooled or artificially-cooled type. It will be more satisfactory, however, to discuss the various types under their descriptive names, bearing in mind that, apart from the plurality of magnetic circuits and windings, the construction of polyphase transformers follows

generally the same details as are presented in single-phase transformers.

Self-cooled Oil Transformers. — The ordinary small capacity transformer is of the self-cooled type. The magnetic circuit is usually a plain rectangle of interlaced strips of iron, permitting a simple form of winding. Fig. 89 shows the elements of such a transformer of the single-phase type. After the coils are assembled on the two vertical legs of the

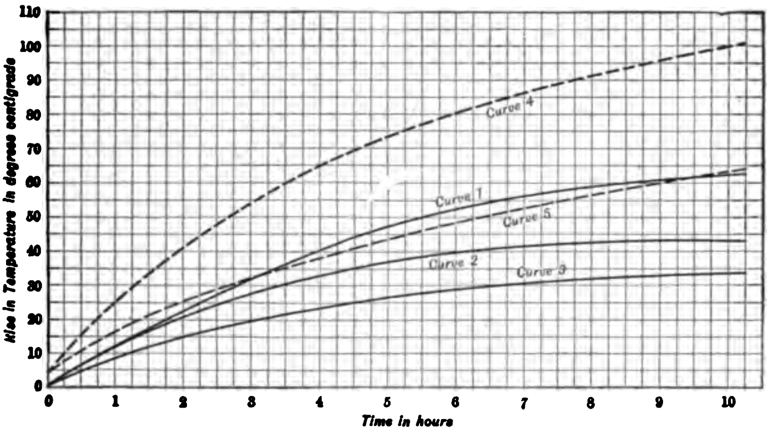


Fig. 90.

core the laminated iron piece seen at the bottom of the figure is connected across the top of the two cores, completing the magnetic circuit. The primary and secondary coils are wound concentrically with an insulating diaphragm and oil space between the two. The laminated iron forming the vertical portion of the core is built up in cruciform section, the recesses at the corners providing channels for the circulation of the oil. A twofold advantage is gained by the use of oil; first, the temperature is reduced

by offering a ready means of escape for the heat; second, punctures in the insulation are immediately repaired by the inflow of the oil.

The reduction in temperature by the use of oil is shown in Fig. 90. Curve 1 gives the rise in temperature of a transformer not submerged in oil, as determined by the increase of resistance method. Curve 2 shows the tem-

Fig. 91.

perature rise of the same transformer immersed in oil. Curve 3 shows the temperature of the oil. Curve 4 is the temperature of the windings of another transformer of poorer design. Curve 5 shows the temperature of this transformer as determined by thermometer. This last curve does not give the true average heating, for the thermometer cannot reach the inaccessible and hottest portions of the transformer.

In transformers of about 50 kilowatts and over, the containing case is usually ribbed or fluted, in order to provide additional radiating surface. The coils and core should also present a large surface to the oil so as to permit the heat readily to be conveyed away from the internal parts. Fig. 91 illustrates a 150 kilowatt transformer of this type built by the Westinghouse Company. The windings

Fig. 92.

are divided into a number of coils, which are spread apart at the ends, thus presenting a large surface to the oil. The heat generated in the iron and in the coils is readily communicated to the oil. The heated fluid rises, flows to the top, and down the sides of the case, which is deeply ribbed (see Fig. 92, showing this transformer assembled in its case), thus presenting a large surface to the air.

The coils and core of a three-phase, 200 kilowatt transformer of different design are shown in Fig. 93. The case of this transformer (not shown) is also of the fluted type.

The essential features of large capacity, self-cooled oil transformers, are high efficiency, corresponding to a mini-

Fig. 93.

mum energy loss to be dissipated in the form of heat; an internal construction which presents the maximum surface of iron and windings to the oil; an arrangement of parts which permits easily to be established the convection currents of the heated oil; and lastly, a ribbed or fluted case, to present the maximum radiating surface to the external air.

Water-cooled Oil Transformers. — When some method for artificially cooling the oil is provided, the generated heat is removed without the aid of natural radiation. The size of tank and quantity of oil may therefore be chosen with reference only to the dimensions of the transformer core and windings and without regard to the amount of surface to be exposed to the air. Also, since the amount of heat which may be developed in the transformer is not limited to the value which can be dissipated by natural radiation, a greater amount of heat may be tolerated. The temperature of the parts may be kept within safe limits since the oil is kept at a low temperature by external means. From the first of these considerations it follows that smaller tanks and less oil may be used; from the second that, where advisable, a higher copper and iron loss, that is, a construction using less copper and iron for the same output may be used. Hence, in sizes which commercially may be constructed in either the self-cooled or the artificially-cooled types, that is, between about 100 kilowatts and 500 kilowatts, the artificially-cooled type will have the advantage of lower cost. This advantage is proportionately greater in the larger sizes. Above 500 kilowatts the self-cooled type is practically non-existent, since not only its cost attains virtually prohibitive figures but also the problem of handling the losses becomes a most difficult one. The general statement may be made that practically all transformers over 250 kilowatts now constructed are of the artificially-cooled type.

Several methods of cooling have been employed. In one type of transformer a supply of cold water is made to circulate through thin flat ducts interposed between the windings. A variation of this arrangement is found in some

low voltage transformers of large capacity, built a few years ago for electric furnace work. The secondary winding of these transformers was constructed of flat copper tubes through which the circulation of water was maintained.

Another form of transformer is cooled by means of a water jacket, surrounding the case containing the transformer proper.

In a third form the method of cooling consists of drawing

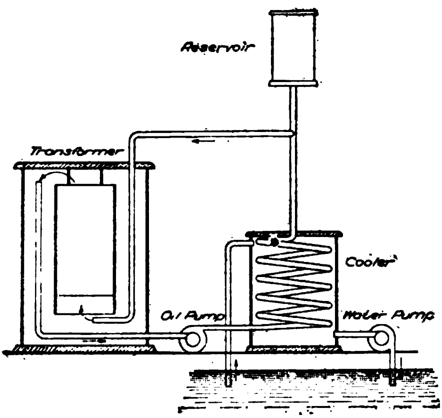


Fig 94.

off the oil, cooling it, and pumping it back. A motor, pump, and system of oil tanks for circulating and cooling the oil are used to control the temperature of the transformer (see Fig. 94). The oil is forced upward through spaces left around and between the coils, overflows at the top, and passes down over the outside of the iron laminations. The advantages of this method are considered to lie in the fact that a brisk current of cold oil is brought directly into contact with the heated transformer parts in such a way as

to absorb the heat most efficiently and quickly. The arrangement is one which would normally find application only in the larger plants where the added cost of the cooling devices would be warranted by the saving in the cost of the trans-

Fig 95.

formers. This method, which of recent years has been but little used, is being again brought forward, and a number of very large transformers have lately been constructed on this principle. These transformers are of the three-phase type,

7500 kilowatts each, and are believed to be the largest transformers ever constructed.

The method most commonly employed cools the oil by means of a worm or system of pipes inside the transformer. A transparent view of such a transformer is shown in Fig. 95. A supply of cold water is circulated through the pipes, seen at the top. Their location just beneath the surface of the oil places them in the most favorable position for carrying away the heat, for at this point the difference of temperature between the cooling pipes and the heated upper layers of oil is greatest. Strong convection currents are thus set up, streams of freshly cooled oil constantly flowing down along the walls of the tank to take the place of the heated oil which rises from the core and coils in the center.

In the transformer shown, which is one of 2000 kilowatts at 60,000 volts, the core and windings are suspended from the cover, so that the internal parts of the transformer may readily be withdrawn for inspection. The tank is of heavy steel plate, riveted and caulked, and a valve in the base permits the oil to be withdrawn if necessary. The ends of the cooling pipe where connection is made to the discharge and supply pipes are taken out through the cover of the transformer.

In Fig. 96 are shown the internal parts, less cooling pipe, of a transformer of the same general design but of the three-phase type. This transformer is rated at 2200 kilowatts, 60,000 volts.

The standard construction of the Westinghouse Company is illustrated by Fig. 97, which shows one of the 3000-kilowatt water-cooled transformers used by the Ontario Power Company in transmitting power from Niagara Falls.

This transformer employs a triple system of cooling pipes of which the supply and discharge connections are seen at the right and left respectively.

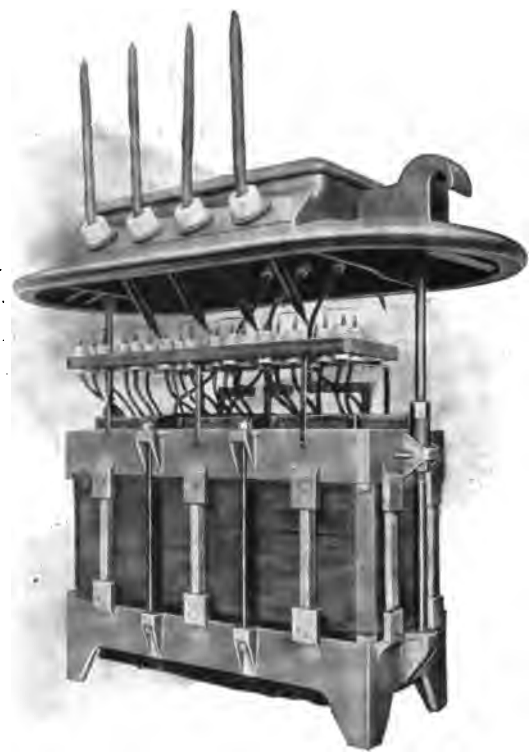


Fig. 96.

Some outside source of power is required to operate the cooling devices, which slightly reduces the total efficiency of the transformation. The water coil may be conveniently supplied by water mains, or, in the case of a water-power transmission, by the water under head.

Oil Type Transformers for High Voltage Testing. — A special type of oil transformer designed to give the very high voltages required in certain testing work is illustrated in Fig. 98. This transformer is capable of producing a

Fig. 97.

maximum sustained potential of 250,000 volts. Distinguishing features of the design are the subdivision of the high potential winding so as to reduce the voltage per coil, and the special form of terminals, which are built up of varnished fabric tubes and filled with oil. This transformer,

as well as most others intended for similar work, is of the core type, with the high tension winding wound outside the low tension coils. The core type adapts itself more readily to the problem of high insulation, which in these trans-

Fig. 98.

formers is one of extreme difficulty, and which is satisfactorily met only by a liberal spacing of the parts and the use of the best materials obtainable.

Quality of Oil Required for Transformer Use. — Oil for use in transformers, particularly at high voltage, requires special care in preparation, selection, and handling.

The two-fold purpose of the oil as a heat conveying, and as an insulating medium, requires that it shall be non-viscous, so that rapid convection currents shall be readily maintained, and that it shall have high insulating properties. Other important characteristics are a high flash-point and an absence of acid or alkaline reaction. Experience has shown that these qualities are possessed only by pure mineral oils of certain grades, specially refined for this use.

While for the most efficient cooling action the oil should be as thin as possible, the ordinary kinds of very light oil are not suitable, for the reason that such are liable to have low flashing and burning points, and may be ignited by a heavily overloaded or defective transformer, or by lightning; or when heated may give off inflammable vapors. The two requirements of high fluidity and low flashing point are in a sense opposed, yet by care in manufacture it has been possible to meet both of these in a satisfactory manner; and instances are very rare where oil transformers made by the best manufacturers have taken fire from any cause.

With the continued increase in the potentials for which transformers were wound, the use of oil, first adopted only as a convenient means of cooling, was found to be a necessity from the insulation standpoint. For potentials much over 35,000 volts there have as yet been found no insulating materials suitable for use in transformer construction that will withstand the high dielectric stress except as aided by immersion in oil. It is the use of oil, therefore, that has made possible the increasingly high voltages which modern conditions demand. For satisfactory results the insulating qualities of the oil must be of the most perfect description. These are secured only by removing the last traces of water,

which is frequently present as an impurity. Oil as furnished by responsible makers of transformers for use with their apparatus has been tested by them for insulation properties and, if necessary, brought up to standard quality by careful drying. Good oil does not absorb moisture by exposure to the air, but water may be present in the containing vessels, or may be deposited from the atmosphere during rapid changes of temperature, or the transformer tanks and parts may be damp before the transformer is filled. All

Fig. 99.

these considerations point to the necessity of thoroughly drying the transformer before the tank is filled and of exercising care in the handling of the oil. When it is considered that even one-tenth of one per cent of moisture renders the oil unfit for use, it will be seen that the condition of the oil must be fully ascertained before it is used. This can be done with certainty only by subjecting it to high potential break-down tests made in accordance with the standards of the transformer manufacturer. If the oil proves deficient it must be dried and again tested before the transformer is

filled. As a final precaution, a sample of oil taken from the filled transformer is tested before the transformer is connected into circuit. These tests, which are simply and easily made, are very necessary in the case of transformers for extra high tension circuits — say 20,000 volts or over —

Fig 100.

and may with advantage be made where the apparatus is intended for much lower voltages.

Air Blast Transformers. — In this transformer the cooling is effected by means of a forced current of air circulating through the windings and core.

The primary and secondary coils are separately wound on

formers and insulated, and then assembled in groups (Fig. 99), the coils being intermingled. The groups are assembled in the form of a case, being separated from one another by vertical air spaces. The magnetic circuit is then built up around the windings (Fig. 100), horizontal ducts being provided at frequent intervals in the laminations.

It is evident that this construction permits the most

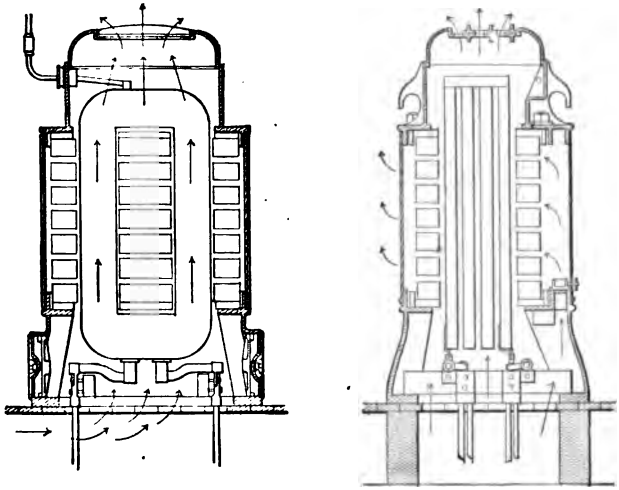


Fig. 101.

complete ventilation, as the very heart of the transformer is reached by the blast of air. The flow of air is controlled by means of two dampers, one of which is located at the top of the transformer, regulating the air between the windings; the other is on the side of the frame, and controls the flow of air through the core. Fig. 101 shows the arrangement of iron and copper parts and ventilating ducts, and Fig. 102 a completed transformer in its frame.

The apparatus for furnishing the air blast consists of a blower, and is usually operated by an induction motor, the

Fig. 102.

air being delivered to the transformer by means of a flue. The volume of air required for cooling purposes varies with the number, size, and efficiency of the transformers.

About 150 cubic feet of air per minute is required per kilowatt loss in the transformer.

The following table gives the volume and pressure of air required for transformers of various sizes of the average efficiency:

Total K.W. of Transformer.	Size of Transformer Unit in K.W.	Cubic Ft. Air Required Per Transformer Per Min.	Cubic Ft. Air Required For Total K.W. Given.	Cubic Ft. Air Furnished by Standard Blower Set.	Ounces Pressure per Sq. in.	Frequency of Circuit.	Size of Blower.	Speed of Blower and Motor.	H.P. to Drive Blower Full Volume and Pressure.
900	100	450	4,050	6,000	½	25	50″	750	2.5
						40	50″	800	
						60	40″	900	
1,800	200	900	8,100	8,000	⅝	25	55″	750	4
						40	55″	800	
						60	50″	900	
2,700	300	1,125	10,125	10,000	⅝	25	55″	750	5
						40	55″	800	
						60	55″	720	
4,500	500	1,625	14,625	14,000	⅝	25	75″	500	6.5
						40	70″	600	
						60	70″	720	
6,750	750	1,875	16,875	20,000	¾	25	90″	500	12
						40	80″	600	
						60	80″	600	
7,500	1,250	2,800	16,800	20,000	¾	25	90″	500	12
						40	80″	600	
						60	80″	600	

From the table it will be seen that the power consumed in cooling the transformers is scarcely one-tenth of one per cent of the output of the transformers. If the transformers have an efficiency of 97.5 per cent at full load, the total efficiency of transformation is reduced to 97.4 per cent by the use of the air blast — a perfectly negligible quantity.

In case of damage to the cooling arrangement, the transformers can operate for a short period without the air blast, but as the transformers are not designed to dissipate their

losses by natural radiation, their continued operation requires an uninterrupted supply of air from the blower, and conservative practice demands that the blower set should therefore be provided in duplicate.

Air-blast transformers are successfully used on voltages up to 35,000 volts. At potentials much above this the difficulties of insulation are considerably enhanced and cannot satisfactorily be met at present except in the oil type of transformer.

In capacities below 100 kilowatts, the design of the air-blast transformer is not favorable to minimum cost, and in most cases the self-cooled oil type will be found cheaper. For this reason the air-blast type is mostly built in sizes above 100 kilowatts. It is well adapted to the largest capacities, and though units having an output of 3000 kilowatts, single-phase, are probably as large as have yet been constructed, larger sizes are entirely feasible.

The approximate weight of transformers of this type is given in the following table, which covers low frequency and high frequency designs:

AIR-BLAST TRANSFORMERS.

Capacity K.W.	Weight in Pounds.	
	25 Cycles.	60 Cycles.
100	3,800	3,000
150	5,200	4,000
200	6,400	5,000
300	8,300	6,500
500	11,600	9,100
750	15,100	12,000
1,000	18,100	14,400
1,500	23,600	19,000

Operation of Air-Blast Transformers. — When transformers of this type are run in groups or "banked" together, care should be taken that the air enters each transformer at the same pressure, otherwise the transformers will take unequal amounts of air and heat unequally. This can be accomplished by having the flue or blast-chamber of such cross section that the velocity of air will not exceed 200 feet

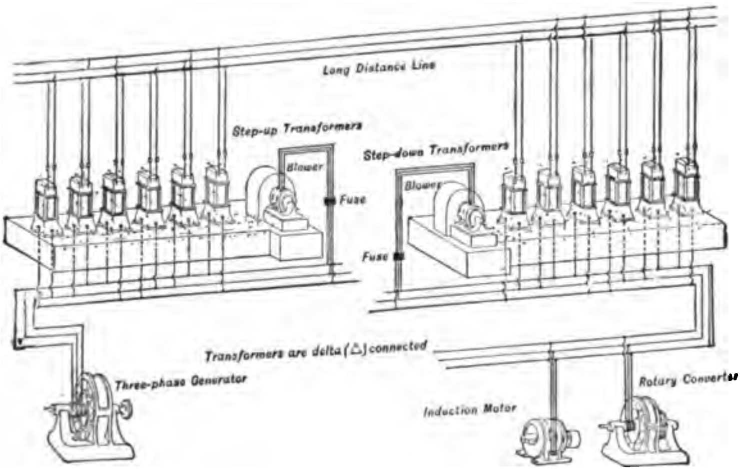


Fig. 103.

per minute. The most desirable installation of the transformer is over a closed chamber of liberal size, which besides keeping the air velocity within suitable limits, will give the added advantage of permitting ready inspection of the windings and connections. Unequal air pressure in different transformers may be compensated for by means of the two dampers. The temperature of the outgoing air affords a ready means of determining the proper amount of

air to be admitted to each transformer. The supply is normally sufficient if the outgoing air is not more than 20 degrees C. hotter than the surrounding atmosphere. Fig. 103 shows the installation and connections of single-phase, air-blast transformers in a long distance power transmission.

Structure of Magnetic Circuit. — It will have been noticed from the illustrations that so far as concerns the arrangement of the coils with respect to the magnetic circuit, all the transformers described conform to one or the other of two general types. These are known generally as the "core" type, in which the coils are assembled around a central core (see Fig. 89), and the "shell" type, in which the magnetic circuit surrounds the coils, as in Fig. 100. Practically all transformers now built may be classed as belonging to one or the other of these two well defined types.

In general, all small transformers, say up to one or two hundred kilowatts, are built in the core type. Among the advantages of this form is the simplicity of construction, which permits easy assembly or dismantling; also, due to the cylindrical shape of the winding, the "mean length of turn" is small, which reduces the resistance and improves the regulation.

In large sizes the core type results in an excessive length of magnetic circuit, and it also becomes troublesome properly to support the vertically disposed coils so as to avoid crushing the bottom turns. Most transformers of large output are therefore built in the shell type, which in large capacities has the advantage of lower cost and a preferable mechanical arrangement. The distinguishing characteristics of this type are the double magnetic circuit of short length, a small magnetizing current, and a disposition of the coils which reduces the magnetic leakage to a minimum.

Efficiency and Losses. — The characteristic efficiency curve of a well-designed transformer shows a high efficiency at all but very light loads. In Fig. 104 the efficiency of a 250-kilowatt, 60-cycle transformer is above 90 per cent even at outputs as low as about $\frac{1}{10}$ load. Good efficiency, at light loads, is a valuable feature, especially in motor and lighting transformers, where the average load rarely makes

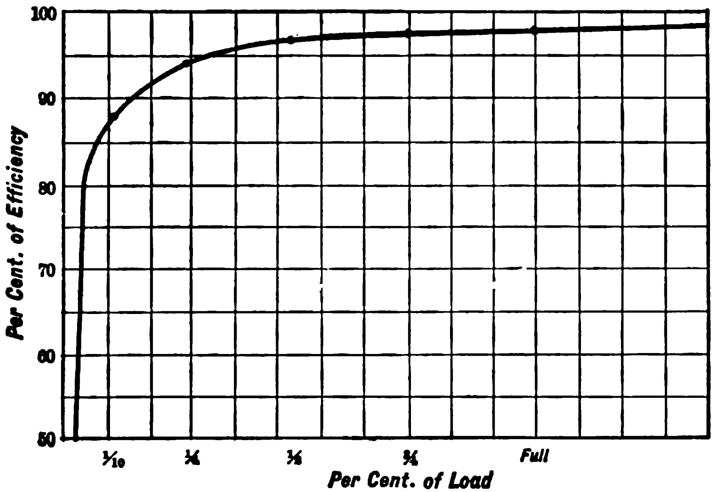


Fig. 104.

a demand of more than one-half of the transformer capacity. The efficiencies taken from the curve, are as follows:

$\frac{1}{10}$ load	87 per cent
$\frac{1}{4}$ load	94.6 per cent
$\frac{1}{2}$ load	97 per cent
$\frac{3}{4}$ load	97.7 per cent
Full load	98 per cent
$1\frac{1}{4}$ load	98.1 per cent

The losses in a transformer consist only of copper and iron losses. The former vary with the load, while the iron

or core losses remain about the same for all loads. It is necessary, therefore, in order to obtain good efficiency at light loads, to reduce the core losses to a minimum. Judging from the shape of the curve in Fig. 104, the core loss must be small. This is shown to be the case in Fig. 105, which gives the watts lost in the iron of the same transformer, and also the corresponding exciting current.

At full voltage the exciting current is 2.3 amperes. The exciting current is the current which the transformer takes at no load, with normal voltage and frequency impressed. It is the vector sum of two currents, viz., the current required to produce the flux in the iron, called the magnetizing current, and the current consumed by the core loss. The latter is an energy current and is in phase with the *E.M.F.* and with the energy component of the load. The magnetizing current is purely wattless and lags 90 degrees behind the *E.M.F.* Ordinarily the magnetizing current will be about three-fourths of the exciting current, and the core loss current about two-thirds of the exciting current, bearing in mind that it is the vector sum of these two which gives the exciting current. From this it follows that with the magnitudes assumed the lag angle of the exciting current is that one having 0.66 for its cosine, or an angle of about 50 degrees. The total current input at any load is the vector sum of the exciting current and the current (lagging, lead-

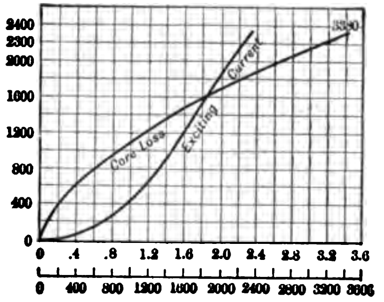


Fig. 105.

ing, or in phase) required by the load. In a well designed transformer the exciting current is small, so that the vector sum referred to is but little greater than the load current. Thus the exciting current adds but little to the copper loss in a good transformer. A high exciting current, in addition to increasing the current input at all loads, means that the transformer will have poor regulation, especially at low power factor.

Again referring to the curves (Fig. 105), the core loss of the transformer in question is seen to be 3380 volts, or 1.3 per cent of the full load input. Since with a full-load efficiency of 98 per cent as shown by the preceding curve, the total losses are 2 per cent of the input, the loss in the copper conductors is the difference, or 0.7 per cent. By reducing the amount of copper in both primary and secondary coils, say one-half, we double the loss in the copper, making it now 1.4 per cent, and reducing the efficiency of the transformer to 97.3 per cent. But the total cost of the transformer is thereby decreased by from 10 to 20 per cent.

It is not always wise to select the more efficient transformer, especially in water-power transmissions, where a large item in the cost of delivered power is the interest on the plant, nor in plants where there is not a demand for every horse power developed. As an illustration, take the case of a power transmission of 1000 H.P. using the cheaper transformer, which has an efficiency of 97.3 per cent. The power delivered is about 1.5 per cent, or 15 H.P., less than with the more efficient step-up and -down transformers. If a market were found for every horse power transmitted at, say $30 per horse power per year, the loss in revenue to the power company would be $450 a year. As a partial offset,

there would be the interest on the difference in the first cost of the transformers. Few water-power transmissions, however, are run at their full capacity. When such is the case, the power company is usually warranted in buying the expensive transformer. In the transmission of steam-generated power, fuel is generally the most important single factor in the make-up of the total cost of power, and, as a rule, the most efficient transforming devices should be used.

Regulation. — Regulation in a transformer is the percentage drop of secondary voltage from no load to full load, the primary voltage remaining constant. Stated in another way, the regulation is the percentage difference between the full-load and the no-load ratio. Good regulation is more desirable in a transformer than in a generator, as there are no means of compounding a transformer for voltage drop. Modern constant potential transformers of the best makes, however, regulate with great closeness, the regulation seldom exceeding 1 per cent except in very small units.

On non-inductive load the regulation is substantially equal to the percentage IR drop in the windings, or, which is the same thing, to the percentage I^2R loss of the transformer, since the value of $\frac{IR}{E}$, which is the regulation, must be the same as the value of $\frac{I^2R}{W}$, which gives the percentage copper loss.

The actual regulation at non-inductive load is somewhat higher than would follow from the foregoing, for the reason that the assumptions made do not take into account the reactance of the transformer windings. In a transformer

having a resistance drop of say 0.5 to 1.0 per cent the reactive drop will be from 2 per cent up to 4 or 5 per cent or even higher, depending on the reactance of the transformer. A reasonable approximation to the non-inductive regulation is obtained by combining at right angles the resistance and reactance drop due to the main current. The vector sum of these is the total, or impedance, drop, which combined with the impressed *E.M.F.* in the proper phase relation will show the resultant *E.M.F.*, from which the regulation is deduced.

Referring to Fig. 106 for the approximate conditions applying at non-inductive load, we have OE, taken equal to 100 per cent, representing the secondary *E.M.F.* of the transformer at full load. In phase with OE is EB, equal to the IR drop of primary plus secondary expressed in percentage of normal volts. At right angles to EB is E_0B, equal to the reactive drop at full load, expressed similarly as a percentage. Therefore EE_0 is the impedance drop through the transformer windings.

Fig. 106.

The resultant of OE and EE_0 is OE_0, which is thus the value of *E.M.F.* which must be impressed to give a full-load voltage equal to OE. If there were no drop, resistance or reactive, the delivered voltage would be the same as the impressed, or equal to OE_0, which can thus be considered as the no load delivered *E.M.F.* Hence the per cent regulation, which is referred to the no-load voltage, is

$$\frac{OE_0 - OE}{OE_0}.$$

With an inductive load at 80 per cent power factor lagging, the conditions are represented by Fig. 107. At 80 per cent power factor the current I lags about 37 degrees behind the $E.M.F.$ The IR drop, equal as before to EB, is in phase with the current I. The reactive drop E_0B is 90 degrees behind the current producing it. Completing the triangles, the regulation is deduced according to the same formula as before. It is obvious that the difference of magnitude between OE_0 and OE is considerably greater than in the previous figure, showing graphically the greater voltage drop (i.e., poorer regulation) with lagging current. Conversely, a leading current with sufficient angle of advance will result in a negative regulation, that is, a higher voltage at full load than at no load.

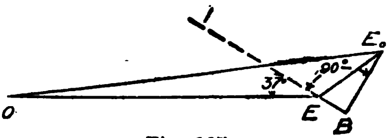


Fig. 107.

Parallel Operation. — For successful parallel operation all the transformers should have the same ratio of transformation and the same regulation. Any transformer in which the ratio is low, which means that the transformer will give too high a voltage on the load side, will tend to set up a local flow of current between itself and the transformers which give a lower voltage on the load side. Full load current, or even more, may thus be made to circulate between the transformers, depending upon the difference in ratio. This will be the condition applying at no load. When it is attempted to take load from two transformers of unequal ratio which are connected in multiple, all the current delivered to the external circuit will be furnished by the transformer which tends to give the higher voltage,

until the voltage drop in this transformer, with the increased current flow, is such as to bring its terminal voltage down to equality with that of the other transformer. The transformers giving higher voltage will therefore under all conditions of load be carrying more

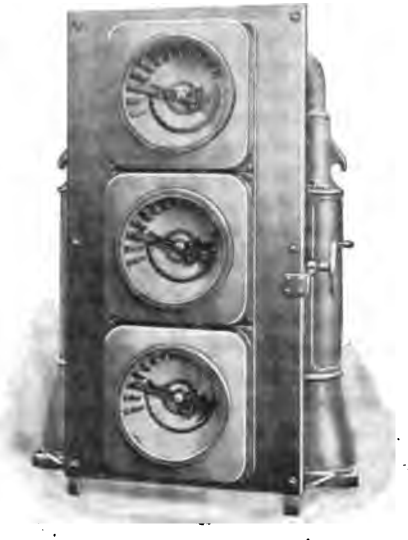


Fig. 108.

than their share of current, with consequent overheating.

Any transformers having a poorer regulation than the others will deliver lower voltage as the load comes on, and thus take less than their share of the load, thereby putting extra load on the other transformers and causing them to overheat.

There is no remedy for inequality of ratio except to make the ratio correct by some means, as by bringing out taps from the windings. Inequalities of regulation can, however, be adjusted by the use of external resistance, or, preferably, reactance, in series with the transformers whose regulation is too close, the external drop thus obtained acting to make the effective regulation enough poorer to result in a satisfactory division of the load.

Change of Ratio of Transformation. — Variations in voltage are sometimes necessary, as, for instance, in the use of rotary converters, where it may be desired to vary the direct-current *E.M.F.* over a wide range. This variation must, broadly speaking, be obtained by a corresponding variation in the *E.M.F.* of the alternating current. One method of varying this *E.M.F.* is to have the transformers so constructed as to permit a change in the ratio of primary to secondary turns. This is accomplished by bringing out taps or loops from the windings and connecting them to a dial switch so arranged that the number of active turns, and thus the *E.M.F.*, is varied by moving the switch to connect with successive taps. Fig. 108 illustrates a three-phase, air-blast transformer arranged in this manner. Each phase has its own dial switch, all three being actuated by a single hand wheel, so that the voltage increase or decrease is effected equally in all three legs of the circuit.

CHAPTER VIII.

ROTARY CONVERTERS.

General. — A rotary converter is essentially a continuous-current generator which, in addition to its commutator, is equipped with two or more collector rings connected to symmetrical points in the armature winding. If such a machine be driven by an external source of power it will evidently deliver either alternating or continuous current, or both. If supplied with electric power it will operate either as a synchronous alternating-current motor, as a continuous-current motor, or as a converter of alternating current into continuous current, or vice versa. Such machines are ordinarily employed to convert alternating into direct current, in which case the alternating current enters the armature winding through the collector rings and is delivered as continuous current after being rectified by the commutator.

When used in the opposite sense, that is, to convert continuous current into alternating current, the continuous current enters the armature winding through the commutator, the alternating current being taken off at the collector rings. When used in this way the designation "inverted converter" is commonly applied, or it is said that the converter is running inverted.

As usually designed, rotary converters differ but little in mechanical construction and in general appearance from direct-current generators. This will be seen from Figs. 109

and 110, which represent two views of a Westinghouse 1500 kilowatt converter. In the design of apparatus of this type, however, certain values for armature reaction and for other constants have been found by experience to be desirable, and these values in general differ considerably from the values of corresponding constants in continuous-current generator design. While, therefore, a continuous-current generator may be made into a rotary converter by the addition of armature taps and collector rings, in the manner described, it is usually not desirable to do so for the reason that without some change in the proportioning of parts and windings a rotary converter so made would probably not give the best results. Furthermore, the number of poles and the speeds for which continuous-current generators are ordinarily constructed correspond to lower frequencies than are commercially used. For example, the frequency of typical slow speed continuous-current generators is usually between 10 and 15 cycles per second, so that it would only be occasionally possible to make from standard generators rotary converters adapted to commercial frequencies.

If the taps from the armature to the collector rings are taken out at points 180 electrical degrees apart, the machine becomes a single-phase rotary converter. Connections at points 90 degrees apart make a two-phase or quarter-phase converter, this connection being essentially a double single-phase arrangement with 90 degrees displacement between the phases. If the connections are made at points 120 or 60 degrees apart respectively, the machine is a three-phase or a six-phase converter.

Connections. — The various connections of the alternating end of rotary converters are diagrammatically shown in Figs. 111 to 118, which also show various practical methods

of connecting converters and transformers together. The circle at the bottom of each diagram represents the armature winding of a bipolar converter, the collector rings being omitted for simplicity.

Fig. 111 shows the connections for a two-phase converter fed by two single-phase transformers. The same sketch,

Fig. 109.

omitting one transformer and its connections, would represent the connections of a single-phase converter.

In Figs. 112 and 114 are shown the connections of a three-phase converter with the transformer secondaries connected "delta" and "Y" respectively.

Fig. 115 shows the diametrical connection of transformers for a six-phase converter. As in the case of the two-phase

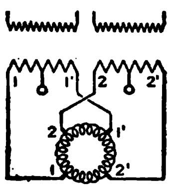
converter, the secondary terminals of a given transformer are connected to points in the armature 180 electrical degrees apart. As the two-phase converter is fed by two single-phase circuits differing in phase by 90 degrees, so the six-phase converter is fed by three single-phase circuits differing in phase from each other by 60 electrical degrees.

Fig. 110.

This is the simplest method of connecting a six-phase converter with its transformer and has the advantage that transformers with single secondary coils can be used.

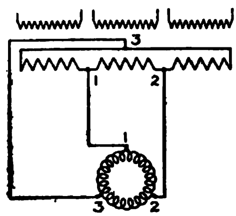
Other connections are also sometimes used, as the six-phase delta and six-phase "Y," shown in Figs. 116 and 118, both of which require two-coil secondaries in the transformers. It will be noted that the delta or "Y" six-phase connection

is, in effect, two three-phase connections applied to the same armature, the connections of one set being reversed. This is true also of the six-phase "T" connection, which is a double reversed three-phase "T" connection, as shown by Figs. 113 and 117. The "T" connection is rarely used,



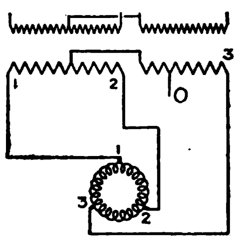
Two-Phase.

Fig. 111.



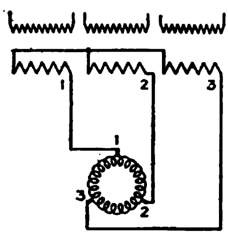
Three-Phase Δ

Fig. 112.



Three-Phase T

Fig. 113.



Three-Phase Y

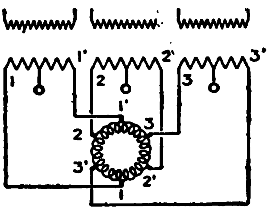
Fig. 114.

as it provides no features of especial merit that are not equally obtainable by simpler arrangements.

In multipolar rotary converters each collector ring is connected to as many points of the armature as there are pairs of poles, that is, the connections must be duplicated for each 360 electrical degrees of the armature.

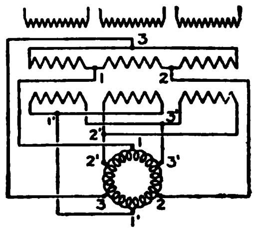
Ratio of Alternating to Direct-Current Voltage. — The

alternating-current voltage of the rotary converter is always less than the continuous-current voltage, the value of which latter is equal to the crest of the *E.M.F.* wave, while the alternating-current voltage corresponds to the mean effec-



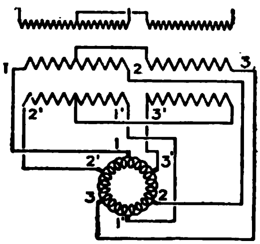
Six-Phase Diametrical

Fig. 115.



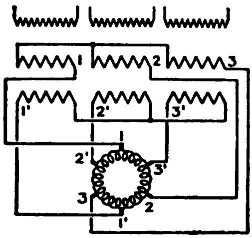
Six-Phase Δ

Fig. 116.



Six-Phase T

Fig. 117.



Six-Phase Y

Fig. 118.

tive value of the wave. The *E.M.F.* induced in the winding of any direct-current generator is alternating in character and is rectified by the commutator when the impulses are at their maximum. The effective value (root mean square) of this alternating *E.M.F.* is $\frac{1}{\sqrt{2}} = 0.707$ of the *E.M.F.* at the commutator brushes, where the alternating *E.M.F.*, as in the case of a single-phase converter, is measured across an

electrical diameter, or 180 electrical degrees. This is the relation between the alternating and continuous voltage of a single-phase, of a two-phase, or of a six-phase diametrical connected rotary converter.

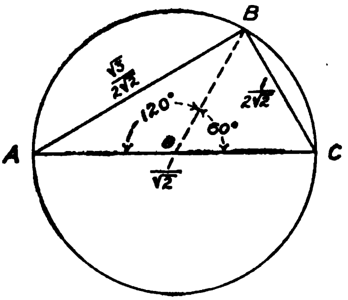


Fig. 119.

If the alternating $E.M.F.$ is measured across some other portion of the armature, this value will be lower. Where the alternating $E.M.F.$ is applied across 120 electrical degrees, the ratio of voltage will be that deducible from the diagram shown in Fig. 119.

Taking the value of the continuous current $E.M.F.$ as equal to unity, let the diameter AC be equal to the measured value of the alternating diametrical $E.M.F.$, viz., $\frac{1}{\sqrt{2}}$.

ABC is a right triangle being inscribed in a semicircle. Further, BC, which is a chord subtending 60 degrees, is equal to the radius, or to $\frac{1}{2\sqrt{2}}$.

$$\text{Therefore } AB = \sqrt{\left(\frac{1}{\sqrt{2}}\right)^2 - \left(\frac{1}{2\sqrt{2}}\right)^2} = \sqrt{\frac{3}{8}} = 0.613.$$

This value, 0.613, is therefore the theoretical ratio for a three-phase converter.

These ratios are the theoretical values applying at no load. At full load they are modified by the magnitude of the IR drop in the armature, which requires a higher alternating $E.M.F.$ to be impressed in order to obtain a given $E.M.F.$ at the direct-current brushes. The effect of this IR

drop is most noticeable in converters of low voltage. The theoretical ratios both at no load and at full load are moreover not always obtained in practice, the departures from the theoretical values being due to a variety of causes acting alone or in conjunction. Among these causes are the percentage of armature circumference covered by the pole faces; the position of the direct-current brushes on the commutator; the shape of the potential wave furnished by the circuit from which the converter is operated; and the amount of excitation.

As the direct-current voltage, neglecting the ohmic drop in the converter, is equal to the maximum instantaneous alternating *E.M.F.* (measured diametrically) that is, to the crest of the alternating wave, it will be seen that a flat top wave gives a lower direct-current voltage with the same impressed alternating voltage, that is, a higher ratio, and a peaked wave under the same conditions gives a higher direct-current voltage, that is, a lower ratio. Further, the shape of the alternating *E.M.F.* wave impressed by the generator upon the converter is modified by the counter *E.M.F.* wave of the converter. A short pole arc on the converter, producing a flat top counter *E.M.F.* wave, thus tends to lower the direct-current voltage at the same impressed alternating voltage, while a long pole arc tends to raise it. That this effect is of marked importance is seen from the example of a recently built six-phase machine of 1000 kilowatts capacity. In this converter a pole arc of 75 per cent was used and the ratio was found to be 0.725. Upon inserting longer pole faces, corresponding to a pole arc of 80 per cent, the ratio then became 0.685. In most commercial machines the percentage pole arc will range between 70 per cent and 80 per cent, and between these

values a given change in the percentage pole arc will produce nearly the same percentage change in the conversion ratio.

Under average conditions of operation the standard types of rotary converters will have at full load approximately the ratios shown in the following table, in which for comparison are also inserted the theoretical no-load ratios based on sine wave *E.M.F.*

Type.	Voltage.	Full-Load Ratios.	Theoretical No-Load Ratio.
Two-phase and six-phase (diametrical)	550 volts	0.725	0.707
	250 volts	0.73	0.707
	125 volts	0.735	0.707
Three-phase and six-phase (Y or delta)	550 volts	0.62	0.613
	250 volts	0.625	0.613
	125 volts	0.63	0.613

These values of the full-load ratio apply to converters of about 25 to 30 cycles. Converters for higher frequencies, as 50 or 60 cycles, having a larger number of poles, are built with a greater distance between pole-tips to minimize magnetic leakage, in other words, with a smaller percentage pole arc, and will in general have slightly higher ratios.

If the direct-current brushes are shifted in either direction from the neutral point, the direct-current voltage is lowered. A change of several per cent in the ratio may be caused in this way, but the amount of variation possible is limited by the amount of brush shift that is permissible within the limits of satisfactory commutation.

A change in the excitation will also affect the ratio slightly. When the fields are strongly excited the direct-current voltage will be somewhat increased by reason of the action of the leading current on the reactance of the armature windings; conversely, a weak excitation which produces lagging

current will cause the direct-current voltage to drop. This effect is, however, trivial, providing that the alternating voltage at the collector rings is maintained constant, and should not be confounded with the effect of leading and lagging current traversing reactance external to the converter, whereby the collector-ring voltage and, with it, the continuous-current voltage, is increased and diminished. This latter effect will be referred to again in connection with the subject of regulation of voltage by field excitation.

In the normal operation of the converter, i.e., when furnishing direct current, the ohmic drop reduces the direct-current voltage. When run as an inverted converter, i.e., when deliveringalternating current—direct current being fed to the brushes — the drop is on the alternating side; consequently the ratio of a converter is lower when run inverted.

For preliminary calculations where the data of operation are not known, the ratios given in the preceding table may be used for most standard converters, though the present tendency is to construct machines with such length of pole arc as will give at full load about the ratios corresponding to the no-load values given.

Where rotary converters are installed in several substations at different distances from the generating station and fed from the same transmission lines, the nearer substations will obviously receive the alternating current at a higher potential than will those more remotely located. In such cases it is customary to equip the step-down transformers with taps in the high-tension winding so that, by selecting the proper tap the same secondary potential may be delivered in each of the substations, thus insuring a uniform direct-current voltage over the system. A range of 10 per cent is the customary allowance in the high-tension trans-

former taps, commonly arranged in four steps of 2½ per cent each. These taps, besides serving the purpose described, are sometimes very useful in compensating for inequalities of the conversion ratio of different converters operated in parallel in the same station.

Ratio of Alternating to Continuous-Current Amperes. — Considering the internal losses as nil, a comparison of the voltage ratios in the several types of converter will show that the following values apply to the relation between the continuous current and the alternating current flowing in each phase:

Type of Converter.	Relative Value A.C. to D.C.
Two-phase	0.707
Three-phase	0.943
Six-phase (delta, Y, diametrical or T)	0.472

These approximate values hold for sine-wave current only and for unity power factor. If the alternating current is not in phase with the *E.M.F.* the above values must be divided by the power factor in order to arrive at the correct ratio.

The value of the ratios given in the table affords a rough means for determining whether the converter is operating at approximately unity power factor, for under this condition, as will be seen, the three-phase current is about equal to the continuous current, the two-phase is about three-quarters of the continuous, and the six-phase about one-half the continuous.

Relative Economy of Material in Different Types. — When in a rotary converter alternating current is being transformed into continuous current, or vice versa, the action of the

machine may be regarded as consisting of a motor action and a generator action taking place simultaneously in the same windings. Hence, the two actions partly neutralize each other, since the alternating current flowing in a given conductor is opposed by the continuous current flowing in the same conductor, and the current actually flowing at a given moment in a conductor is approximately equal to the difference between the value of the continuous current and the instantaneous value of the continually changing alternating current. This net value in a polyphase converter is always less than the value which would flow in the conductors if the converter were operated as a generator driven mechanically from an external source of power. From this it follows that for the same I^2R loss the armature conductors of a polyphase converter can be made of smaller cross section than in a generator of equal output. The greater the number of phases for which a converter is wound, the greater will be this saving, because with many phases the path through the armature between alternating and continuous current terminals is shorter and more direct. The approximate relative amount of this saving is indicated in the following table, which shows the capacity in kilowatts which could be delivered by various types of converters, assuming that they all contain the same weight of armature copper as would be required in a generator of 100 kilowatts capacity, which is taken as the basis:

Type of Machine.	Capacity.
Continuous current generator	100
Three-phase converter	131
Two-phase converter	161
Six-phase converter	194

Since the foregoing table is based on considerations of armature copper alone, and does not take into account other electrical or mechanical parts of the machine which are not affected, it follows that the several weights of a given converter when designed alternatively for two-phase, three-phase, or six-phase connection, will not show as great a difference as do the several capacity ratios given in the table. Nevertheless, the progressive reductions in the amount of armature copper as the number of phases is increased operates of itself to reduce the aggregate weight of the machine, both as a result of the diminished weight of the conductors and as a result of the somewhat smaller armature diameters which can be used to advantage when the number of phases is increased. Another advantage secured by increasing the number of phases, is that the tendency to pulsation is reduced owing to the more uniform turning moment, which follows from the fact that the number of impulses per revolution is greater. An increased number of phases tends also to improved commutation.

The capacity ratios in the table referred to are based on non-inductive load. Where the current is lagging or leading, the armature heating, for the same continuous current output, is increased, and the capacity ratios thereby proportionately reduced. The wattless component circulates through all conductors in series between phases, and thus over a path of higher resistance than does the energy component flowing from collector rings to commutator. A given intensity of wattless current will therefore cause a greater loss of power in resistance than will the same intensity of energy current. From this is explained why, with a given increase in the alternating current input due

to phase displacement, the increase in heating, and reduction in capacity, is greater than would at first seem to be reasonable, having reference only to the relative squares of the current values corresponding to the non-inductive and to the inductive condition respectively. In this connection the following example is cited: By the preceding table the capacity ratio for a three-phase converter at non-inductive load is 1.31. Assume now a phase displacement giving a wattless current equal to 30 per cent of the input. The total current being 100 per cent, the energy current, which is in quadrature with the wattless current, will be 95.4 per cent. We should expect an increase of heating in the ratio of $\overline{100.}^2$ to $\overline{95.4.}^2$, or, which is the same thing, that the capacity for the same heating would be reduced in the proportion of 95.4 to 100, that is, by 4.6 per cent. If this were true the capacity ratio of the converter would become

$$1.31 \times 0.954 = 1.25.$$

Instead of this it is found that the capacity ratio is reduced over 8 per cent, or to 1.20. Steinmetz (Elements of Electrical Engineering) calculates the following values of the capacity ratio with 30 per cent wattless current. The unity power factor capacity ratios from the preceding table are repeated for comparison.

Type of Machine.	Capacity.	
	30% Wattless Current.	Unity Power Factor.
Continuous current	100	100
Three-phase converter	120	131
Two-phase converter	145	161
Six-phase converter.	170	194

Since 30 per cent wattless current corresponds to a power factor of 95.4 per cent, it is seen that even a comparatively small departure from non-inductive conditions causes a marked increase in the resultant heating. At 90 per cent P.F., corresponding to about 44 per cent wattless current, the condition is further aggravated, and the three-phase converter capacity ratio thereby reduced to 1.16. From this it is evident that the heating of a converter is notably sensitive to changes in power factor, and that when a phase displacement exists the reduction in effective capacity is more marked than in other types of synchronous machines. Hence, where converters are to be used, like synchronous motors, for phase control, it is important that due provisions should be made in the design.

Regulation of Voltage. — Mention has been made of the fact that so long as the impressed alternating *E.M.F.* remains constant, little change can be brought about in the continuous current *E.M.F.*, either by change of excitation or by brush shift. Stated in another way, this means that the voltage conversion ratio of a given machine is practically a fixed quantity, and that to increase or decrease the direct current *E.M.F.* by any considerable amount a corresponding increase or decrease must be brought about in the alternating *E.M.F.*

This may be effected by the use of a potential regulator inserted in the alternating-current leads. This method is mostly used where a wide voltage variation has to be accomplished while the converter is carrying load, and where a fine and smooth adjustment is demanded, as in lighting service.

Another method calls for the provision of taps or loops in the windings of the transformers which feed the con-

verter. These taps give a step-by-step change in the transformation ratio and thus a corresponding change in the delivered secondary potential. To effect quickly the desired adjustment these taps are connected to a dial switch located on or near the transformer. This method, like that referred to in the preceding paragraph, can be employed to give any desired range of adjustment, but is not so well adapted for use when the converter is carrying load on account of the sparking which takes place at the contacts when the position of the switch is changed. Unless the switch is designed to pass very quickly from point to point, there is also the possibility that the converter may fall out of step in the interval during which the circuit is momentarily opened. By this method of regulation the potential is changed in a series of abrupt and definite steps and not smoothly as with the method first described; and while the number of taps may be made sufficiently great to give only a small variation between steps, this method has only a limited application, for the reason that when the number of taps is made very large the added cost and complication in the transformer becomes excessive.

The third method makes use of the property which the converter, like the synchronous motor, possesses, namely, that of producing a phase displacement by change of field strength. Thus the current may be made to lag or to lead according as the field is under-excited or over-excited.

Now, the *E.M.F.* of self-induction lags 90 degrees behind the current producing it. Hence, with lagging current and a phase displacement of 90 degrees, the phase of the *E.M.F.* of self-induction will be 180 degrees behind that of the impressed *E.M.F.*, that is, directly opposed to it, and the resultant *E.M.F.* will be the difference between the two.

Similarly, when the current is leading by 90 degrees the *E.M.F.* of self-induction will be in phase with the impressed *E.M.F.* and additive directly thereto. For phase displacements less than 90 degrees the effect will be similar, though of diminished magnitude. With sufficient self-induction and with the amount of phase displacement feasible to obtain in practice it is possible to effect by this means a potential variation of from six to eight per cent, and sometimes more, under favorable conditions. This method of voltage control will be considered again, and with a numerical example, in a later paragraph.

Rotary converters are commonly arranged either for shunt or for compound-wound fields. In the former case the field coils are connected across the direct-current brushes, while in the latter case a series winding is provided in addition to the shunt excitation. The field connections in either case are precisely similar to those of shunt or compound wound continuous-current generators.

Shunt-Wound Converters. — In the shunt-wound converter, for any given setting of the field rheostat, the field strength remains practically constant for all conditions of load. Since the magnitude of any phase displacement, as well as its direction, that is, lagging or leading, is dependent on the field strength, it follows that in this type of machine any given phase displacement will remain unchanged irrespective of the load — in other words, that the converter will operate at practically constant power factor. This power factor may be unity, or the current may be made always lagging or always leading, dependent on the value of field strength given to the converter. This property is graphically shown in Fig. 120, which represents several phase characteristics of a 100 kilowatt, three-phase,

550 volt machine. Each curve shows the variation in the alternating-current input for varying field strengths at different loads, the continuous current output for the conditions represented by any particular curve being maintained constant at the value appearing directly above each curve.

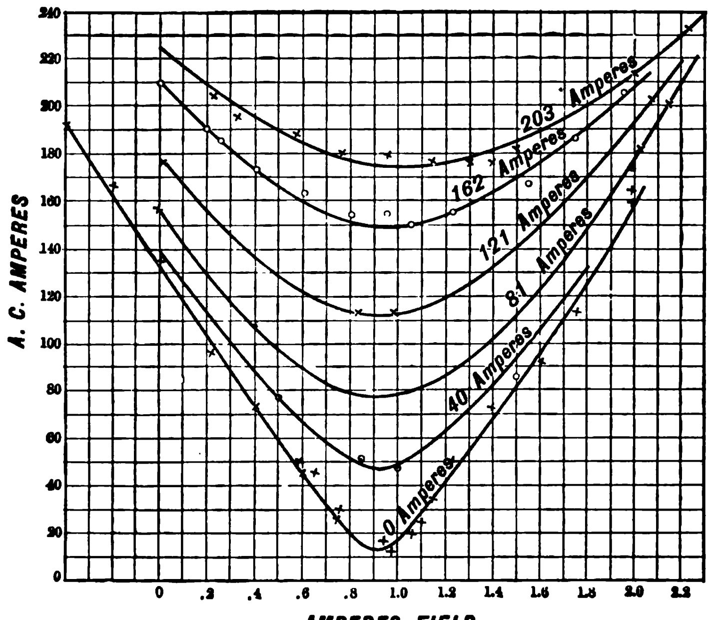


Fig. 120.

The field strength for minimum current input, or 100 per cent power factor, is 0.92 ampere at no load, and about 0.95 ampere when the continuous current output has been increased to 203 amperes, or to about 10 per cent overload (which happens to be the load at which the highest curve was taken). This small increase in field current necessary

to maintain unity power factor proves that the armature reaction is very slight.

This property is shown in another way by the field characteristic curve of the same 100 kilowatt converter, represented in Fig. 121. Through a range of output between no load and about 20 per cent overload this curve shows the increase in field ampere turns necessary to maintain unity power factor, the potential at the direct-current brushes

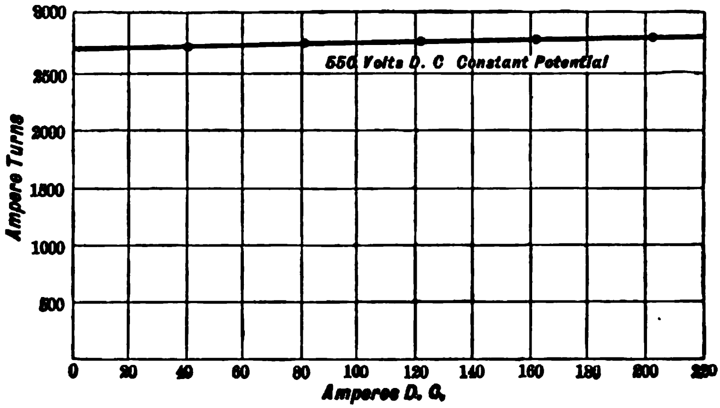


Fig. 121.

being maintained constant at 550 volts. The ampere turns at no load are 2700 and at an output of 203 amperes are 2800 — an increase of about 3.7 per cent. The ratio of increase in the ampere turns is of course the same as the relative increase in the amperes field, as shown in the phase characteristic of Fig. 120, both curves being plotted from the same tests.

It is therefore seen that the characteristics of the shunt-wound converter in the matter of keeping the power factor practically constant over wide ranges of load insure that

the delivered direct-current potential shall be practically constant, provided that constant potential be delivered to the high tension side of the step-down transformers. It follows equally that variations in the high-tension alternating pressure will reappear in the form of proportionate variations in the direct-current voltage, the ratio of transformation in the step-down transformers and the conversion ratio of the converter itself both being practically constant. Since variations in the high-tension voltage received by the transformers are caused chiefly by changes in the line drop incident to fluctuations in the load, the shunt-wound converter is not therefore the advantageous type where a constant direct-current pressure is desired over considerable ranges of fluctuating load. The exception to this is the case where the changes of load are gradual enough to permit the voltage to be readjusted by hand, by any of the several methods referred to in the preceding section. To conditions of this character the shunt-wound type is well adapted, and it is therefore frequently used on large systems where the changes of load take place slowly, or where it is important to maintain constant conditions of power factor.

Compound-Wound Converters.—In the compound-wound type the strength of the field increases with increase of load, due to the added ampere turns produced by the series winding. Hence, if at no load the shunt field is adjusted to produce a lagging current, the progressive building up of the field as load comes on will diminish the phase displacement and finally bring the current into phase with the *E.M.F.*, or even cause it to lead the *E.M.F.* if the series winding is strong enough. In this way, by altering the angle of phase displacement, the *E.M.F.* of self-induction

combining with the impressed *E.M.F.* will tend progressively to raise the voltage at the collector rings with increase of load, thereby effecting a corresponding increase in the direct-current potential.

Compound-wound converters are therefore used to advantage where, with fluctuating loads, it is desired automatically to control the voltage delivered from the direct-current terminals. The conditions of railway work are usually of this kind, and it is here that the compound-wound converter is most, and almost exclusively, employed.

In order to show the relation of the various factors which give these results, we will take the case of a quarter-phase converter designed for an output on the direct-current side of 300 kilowatts at 600 volts. In the numerical example which follows it will be assumed for the sake of simplicity that constant voltage is maintained on the secondary terminals of the transformers from which the converter is fed, and that the various data are as follows:

ROTARY CONVERTER, QUARTER-PHASE.

Capacity	300 kilowatts
Efficiency, full load	0.93
Conversion ratio, A.C. ÷ D.C.	0.71
Volts, D.C.	600
Volts, A.C. (600×0.71)	426
Volts at transformer secondary held constant at	426
A.C. amperes full load, $\frac{300000}{2 \times 426 \times 0.93}$ =	378
A.C. amp. no load, $\frac{0.07 \times 300000}{2 \times 426}$ =	24.6
Voltage consumed at 378 amp. by self-induction of circuit between secondary terminals of transformer and converter collector rings, assumed to be equal to 15 per cent of secondary *E.M.F.* of transformer, or 0.15×426 =	64.

Let us suppose the converter to be running at no load, that is, with zero output from the D.C. side, and with the field strength adjusted for unity power factor. Let the field now be weakened until the current input rises to, say, 30 per cent of the full-load non-inductive amperes, or to $0.30 \times 378 = 114$ amperes. Since the energy current required at no load is but 24.6 amperes and since by producing a heavy lagging current the input, still at no load, has been raised to 114 amperes, it follows that the power factor has been reduced from unity to 0.216 (equalling $24.6 \div 114$) and that the angle by which the current is lagging behind the *E.M.F.* is that angle whose cosine is 0.216, or about 77 degrees.

We are now ready to construct the diagram of Fig 122, which shows the various *E.M.F.'s* of one phase.

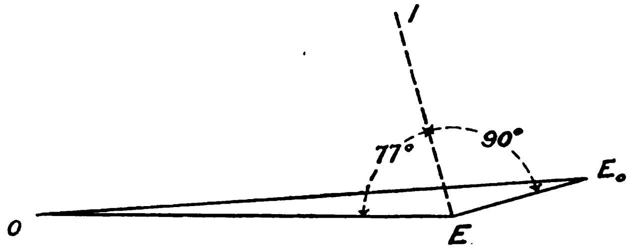


Fig. 122.

On the base line *OE* draw *EI* so that angle *OEI* equals 77 degrees, *OE* representing the *E.M.F.* impressed on the collector rings, and *EI* representing the current lagging 77 degrees behind it. Since with full-load current the *E.M.F.* of self-induction is 64 volts, and since at no load the current input has been made equal to 30 per cent of the full-load current, the *E.M.F.* of self-induction at no load will be $0.30 \times 64 = 19.2$ volts. EE_0 is accordingly drawn 90 degrees behind *EI* and equal to 19.2.

In the triangle OEE_0, OE_0 will therefore represent the value of the *E.M.F.* which the transformer secondary must deliver in order that an *E.M.F.* equal to OE shall be delivered to the collector rings; or, which is the same thing, if OE_0 is drawn equal to the transformer secondary *E.M.F.*, or 426 volts, the length of OE will represent the *E.M.F.* that is delivered to the collector rings. Solving the triangle, OE is found to be 408 volts. This being the A.C. volts, division by the ratio 0.71 will give the voltage at the commutator. Thus, under the conditions assumed, the D.C. voltage at no load is determined to be 575 volts.

At full load let it be assumed that the added field strength due to the series winding is slightly more than sufficient to bring the current into phase with the *E.M.F.*, and that in fact a small angle of lead results, say five degrees. The full-load diagram, Fig. 123, can now be drawn as follows:

On OE draw EI as before, only now instead of lagging 77 degrees the current is leading by 5 degrees. Draw EE_0 90 degrees behind EI and equal to 64 volts, which is the *E.M.F.* of self-induction at full load. Draw E_0O equal, as before, to the transformer secondary *E.M.F.*, viz., 426 volts. Then OE will be the *E.M.F.* delivered to the collector rings. With the values as chosen, a solution of the triangle OEE_0 will give OE equal to OE_0, and the collector-ring voltage will thus be 426 volts, corresponding to a direct-current pressure of 600 volts.

It is thus seen that with constant *E.M.F.* at the secondary terminals of the step-down transformers, the direct current *E.M.F.* of the converter increases from 575 volts at no load to 600 volts at full load, an increase of 4.35 per cent. The

condition of constant secondary transformer potential is, however, seldom met in practice on account of the voltage drop in the transmission lines due to the load. Hence, assuming a loss of 4.35 per cent in the high-tension feeders, the secondary voltage of the transformers will be 4.35 per cent lower at full load than at no load; and this fall of potential will offset the increase of voltage at the collector rings which would otherwise follow. Therefore, taking into account both the line loss and the control of voltage through the action of phase displacement, as just explained, the delivered direct-current potential will be the same at full load

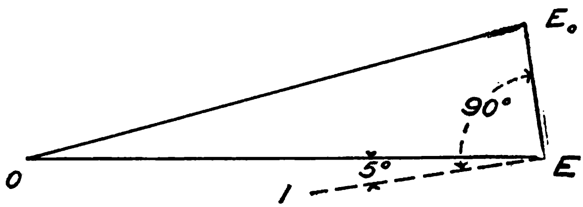


Fig. 123.

as at no load, the condition in this case corresponding to the action of a continuous-current generator compounded for constant voltage. Similarly, if the line loss is greater than can be compensated for by the phase displacement, the voltage at the D.C. brushes will fall off with increase of load, while if the line loss is less, a small over-compounding is obtained.

The converter having supplied to it a given voltage on the alternating end will deliver a given voltage on the direct-current end, depending on the practically constant and fixed value of the conversion ratio; and the variation in the delivered D. C. pressure is due not to any addition of vol-

tage within the converter, but to the action of the converter in producing a difference in the phase displacement, as a result of which a change is brought about in the voltage which is delivered to the converter. It is thus seen that it is in reality not the converter which is compounded, but rather the system as a whole.

In the example worked out above the calculation was based on an *E.M.F.* of self-induction equivalent to 15 per cent of the normal potential. To obtain in ordinary working a reasonable range of voltage control without excessive variations in power factor, converters for 25-cycle circuits should operate on a reactance of from 17 to 20 per cent. For higher frequencies this value is usually somewhat lower on account of possible difficulties from pulsation which are aggravated when the reactance is too great. The self-induction of lines, transformers, and connections, taken collectively will seldom exceed 5 to 7 per cent under normal conditions, so that artificial reactances are frequently inserted sufficient to bring the total up to the desired value. These may be connected at any point in the circuit between generator and converter, but are almost invariably connected between the transformer secondaries and the collector rings, where they give the advantage of individual voltage control to converters operated in parallel and where their windings are subjected to only moderate potential strains.

Power Factor. — Owing to the small and practically negligible armature reaction, there will be little change in power factor with change of load, provided that the field strength is kept constant. A uniform, though adjustable, power factor is therefore the characteristic of the shunt-wound type, while the compound-wound machine with its varying excitation gives a variable power factor, the amount

of variation with change of load depending on the relative strength of the shunt and series windings. As commonly adjusted, compound converters will give a power factor of unity at about full load when arranged for flat compounding with 5 per cent line drop and with a total reactance in circuit of 18 per cent. Under conditions where a greater compounding can be obtained, the series field will be adjusted to give unity power factor at about three-quarters load. In either case the power factor at light load will be rather low, the current at no load, as shown in Fig. 122, being almost wholly wattless. A variation of the reactance in the supplying circuit will change the values of the excitation that must be furnished to produce unity power factor on the system at any particular load. This is for the reason that the *E.M.F.* of self-induction varies with the reactance, and on it depends the value of the wattless lagging component of the main line current, which is to be neutralized by the equal and opposite wattless (leading) component which the converter must produce if unity power factor on the system is to result.

The small amount of armature reaction present in rotary converters is explained by the fact that the two distinct actions, motor action and generator action, which take place simultaneously in the armature, are of opposite sign and thus virtually neutralize each other. The net result is that the behavior of the machine considered as a converter is practically that of a machine in which armature reaction is absent. Considering the converter as a generator, the armature reaction may be, and frequently is, quite high, higher in most cases than would be advisable in a continuous-current generator of equal capacity and speed. When the armature reaction of a converter is referred to

quantitively it is the armature reaction of the machine considered as a continuous-current generator that is meant.

Although through the counteracting influence of the two opposing currents the effective reaction is made almost nil, there yet remains a small residual, namely, that due to the current required to supply the losses of the machine. Hence, it is usually desirable to give the direct-current brushes a slight amount of shift to bring them into the best position for commutation. When the converter is used in the ordinary sense, that is, to convert alternating into continuous current, the direction of the brush shift is forward, or in the direction of armature rotation, while for inverted operation the direction of shift is in the opposite sense, or against the direction of rotation.

Limit of Frequency. — The limit of frequency of a rotary converter is determined by mechanical considerations. In designing a machine for a given number of alternations, the problem is to keep the peripheral speed of the commutator within practical limits. Too high a peripheral speed will cause the commutator segments to buckle, through the action of centrifugal force. A reduction in the diameter of the commutator, on the other hand, may reduce the width of the segments below the lowest limit fixed by experience with commutator construction and operation. The voltage and output will determine the general dimensions of the commutator. Take the case of a 600-kilowatt, 550-volt, 60-cycle rotary converter, the speed of which, on account of its size, is limited to, say, 600 revolutions per minute. The number of poles would be 12. The peripheral speed of the commutator being limited, the circumference is at once fixed. The average volts per bar being also limited, the total number of seg-

ments is determined. In a 40-cycle rotary recently constructed, the average voltage between segments was limited to $13\frac{1}{4}$ volts, and the commutator speed to 4500 feet per minute. If we apply this data to the 60-cycle converter, we have the following:

Number of segments between poles = $550 \div 13\frac{1}{4} = 41$.
Total number of segments = 12 (number of poles) $\times$ 41 = 492.

That circumference of the commutator which will keep the peripheral speed within the limits set — i.e., 4500 feet per minute — is 90 inches, thus allowing only 0.18 inch for the width of each segment. For mechanical reasons this width is less than can be used. It will be seen that, unless the speed can be increased, thus permitting a smaller number of poles, or the peripheral speed of the commutator can be increased, permitting a larger circumference, and consequently wider segments, the difficulty can be overcome only by using two commutators, each delivering 275 volts and connected in series for 550 volts. This, however, involves a complication of collector rings and connections, and the current must be commutated twice and the commutator losses doubled. This converter could be built readily with one commutator if wound for 250 volts or thereabouts. The general statement may be made that for frequencies over 35 to 40 cycles it is more difficult to build converters for high voltage than for low voltage — i.e., for, say, 600 volts, than for 100 to 200 volts — but not such a difficult problem to wind a converter of less than 35 cycles for the higher voltage.

The following table shows the speed and approximate weight of railway service converters of a standard make for various outputs and for frequencies of 25 and 60 cycles:

25-CYCLE CONVERTERS.

Poles.	Capacity K.W.	Speed R.P.M.	Weight Pounds.
4	200	750	15,000
4	300	750	20,500
6	400	500	30,000
6	500	500	35,000
6	750	500	45,000
8	1,000	375	58,000
12	1,500	250	92,000

60-CYCLE CONVERTERS.

6	100	1,200	7,000
6	200	1,200	11,000
8	300	900	18,000
12	500	600	33,000

Parallel Operation. — The conditions of service require that converters should be able to work in parallel with one another, and they can be so operated with entire facility. To insure proper division of the load each converter should obviously deliver the same direct-current voltage. This demands either that the conversion ratios of all the machines should be the same or that the voltage delivered to the collector rings should be such that any difference of ratio will be compensated for. The usual arrangement is to feed each converter from its own bank of transformers. This plan saves the cost and complication of low tension A.C. bus bars and dispenses with switches and measuring instruments in the low-tension circuit. It has the further advantage that it permits some independent voltage adjustment to be given to each converter, through the fact that a phase displacement following a change in excitation acts on the self-induction of a local and independent circuit. The

range of individual voltage adjustment is greatest for a condition of maximum self-induction, corresponding to the use of the artificial reactance supplied for compounding. Under this condition it is frequently possible to equalize the D.C. voltage and the load even where the conversion ratio or the ratio of the step-down transformers, is several per cent off.

Starting of Rotary Converters. — Rotary converters may be started by auxiliary motors after the manner already described for synchronous motors. In this case the converter, after being excited, has to be synchronized before being connected to the alternating-current supply.

Converters may also be started from the direct-current end, in the same way as a direct-current shunt or compound-wound motor. This mode of starting also requires the machine to be synchronized, the necessary adjustment of speed being accomplished by variation of the shunt-field strength.

The objections to methods of starting which require synchronizing are that considerable time may be required for getting the machine in service, particularly where, as is frequent in railway work, the line voltage or frequency is unsteady, due to fluctuations in the load. Unless it is important to keep the starting current within the lowest possible limits, therefore, the most convenient method of starting is to apply alternating voltage direct to the collector rings of the converter, the converter thus starting like an induction motor. Under these conditions the starting torque is made reasonably good by the use of solid poles, or if the poles are laminated, by the use of bridges or a short-circuited "amortisseur" winding. One or the other of these constructions is usually employed in any event, as

their tendency is to minimize troubles from hunting and to improve the stability.

The voltage to be applied at starting may be reduced by a compensator, or, since transformers are nearly always used with rotary converters, by the use of fractional voltage taps in the secondary winding. With converters of 400 kilowatts and under a single tap at half voltage is usually provided, while with converters of over 400 kilowatts two taps are advisable, at ⅓ and ⅔ voltage. One or two double-

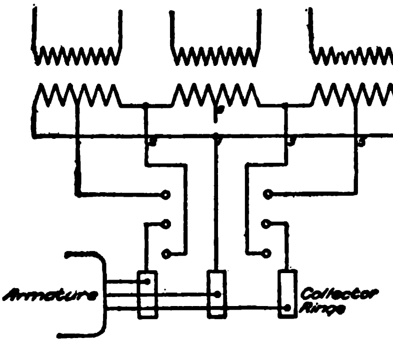


Fig. 124.

throw switches, dependent upon the number of taps brought out, are used, as shown in Figs. 124 and 125. In Fig. 124, showing the connections of a three-phase converter, its transformers having half voltage taps, a double-pole, double-throw switch is used. Referring to the diagram, when the switch is in the "up" position, half voltage is impressed on the collector rings, and when the switch is thrown down full voltage is impressed. In Fig. 125, which shows the connections of a six-phase machine with transformers having ⅓ and ⅔ taps, two triple-pole, double-throw switches are used. In starting, both switches are thrown to the "up" position,

thus applying $\frac{1}{3}$ voltage. The next step is to throw the left-hand switch to the "down" position, which applies $\frac{2}{3}$ voltage. Finally, the right-hand switch is thrown to the "down" position, which impresses full potential across the collector rings.

Well designed converters when started from the alternating-current side in the manner described, will draw not more than about full-load current from the line. Where

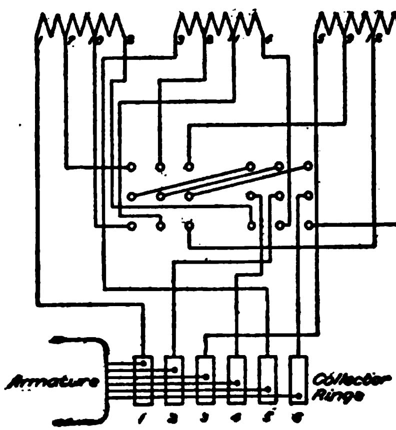


Fig. 125.

converters are started in this way there is an equal chance that the polarity of the direct-current brushes will be right or wrong. In the event of the converter's locking itself into step with the direct-current potential reversed, the polarity may be corrected by separately exciting the fields of the machine from the bus bars. This should be done while the collector rings are receiving their current from the low-voltage tap on the transformer. This is more conveniently accomplished, however, by the use of a double-

throw type of field switch in the self-exciting circuit, so that from the terminals of the machine itself current may be sent through the fields in either direction. In this way a change of polarity can be effected without recourse to an external source of current. Where this switch is called into play it should also be used while the converter is running at low voltage, since an attempt to reverse the field at full voltage not only causes bad sparking at the commutator but would probably prove unsuccessful, the reason being that the synchronizing power with full alternating voltage applied, due to the induced field set up by the armature current, is too strong to permit the relative retrograde movement of the armature that takes place on reversal of polarity.

The field switch, whether of the double-throw type or not, should be made with several blades and contacts, so that when open the field circuit is divided into sections, as shown in Fig. 84, in order to minimize the voltage induced in the field winding at starting.

Equalizers must always be used where compound-wound converters are run in parallel, as is usual with compound-wound, continuous-current generators.

A compound-wound converter, when operating in parallel with other machines, will take current from the bus bars and run as a direct-current motor if its voltage is low, or if the alternating-current side is disconnected from the A.C. supply, or in the event of a short circuit in the alternating-current leads or windings. The direction in which the series coils are wound, while adding to the field strength when the machine is delivering current, will act in opposition to the excitation of the shunt coils when current is flowing into the machine; and if the machine has a strong series winding it is likely therefore to increase greatly in speed

when running in this way as a direct-current motor. To guard against this, compound converters are desirably provided with some form of centrifugal device which, by closing an auxiliary circuit, will trip the direct-current circuit breaker at a predetermined increase of speed.

Rotary converters are also commonly provided with a small mechanical oscillator, or end-play device, acting on the end of the shaft, to give the shaft a small reciprocating motion in the bearings. The action of this device prevents the rubbing parts, such as commutator, collector rings, and bearings, from wearing in ridges or grooves, which would be liable to form in the absence of any end-play.

Hunting. — Hunting of rotary converters is caused by the same conditions that similarly affect synchronous motors, and is corrected by similar expedients. Variation in the turning moment of the prime movers, short circuits, sudden changes of load, too high resistance in the transmission lines, defective design of the converters, are all factors which affect the stability. The hunting tendency naturally increases with the frequency. At 25 cycles stability may be readily obtained. The problem is rather more difficult at 60 cycles, and requires skillful attention and careful adjustment to local conditions.

Inverted Converters. — When running inverted, that is when converting from continuous to alternating current, the speed of the converter, as in a direct-current motor, depends upon the field strength, being increased by a weak field and decreased by a strong field. A change in the setting of the field rheostat therefore affects only the delivered frequency and not the voltage, the A.C. voltage being determined only by the product of the direct-current voltage into the conversion ratio of the machine. A con-

verter intended to run inverted should have little or no series field, or it will change in speed with variations of load and thus deliver an unsteady frequency. If an inverted converter is supplying current to an inductive circuit, the lagging current delivered, which is demagnetizing in its action, tends to weaken the field strength and hence to increase the speed. Under extreme conditions, the reduction in field strength may be sufficient to cause an excessive rise in speed. An efficient form of speed limiting device is therefore especially important for converters when run inverted.

Double-Current Generators. — This term is applied to generators designed to give either alternating or continuous current, or both alternating and continuous current at the same time. They may be wound for any desired number of phases on the alternating end and on the direct-current end for any voltage within the limits of continuous-current design, the ratio between the alternating and the direct-current voltage being essentially the same as in a converter of the same number of phases. They have the general appearance of rotary converters, being equipped with a commutator on the direct-current end and with collector rings on the alternating-current end, but have in addition the necessary mechanical parts, such as are provided with generators, to adapt them for mechanical driving. They are most conveniently constructed for fairly high speeds because if built for a low speed the large number of poles that is necessary to bring the frequency within commercial limits results, for ordinary sizes, in a very thin or narrow armature and an uneconomical construction.

Double-current generators are designed with much lower armature reaction than rotary converters. The field cir-

cuit may be designed for excitation from the direct-current brushes, but where a considerable proportion of the output is to be delivered in the form of alternating current the reaction on the field under conditions of inductive load lowers the direct current *E.M.F.* This in turn reduces the excitation and magnifies the fall of potential with increases of load. For these reasons separate excitation is usually desirable.

CHAPTER IX.

MOTOR GENERATORS, FREQUENCY CHANGERS, AND OTHER CONVERTING APPARATUS.

In the conversion of electrical energy from one voltage or frequency into some other voltage or frequency, either a single apparatus may be used specifically adapted to the purpose, or a combination of two or more machines or pieces of apparatus may be employed. For converting alternating into continuous current, for example, a rotary converter * may be used, or the conversion may be effected by the medium of an apparatus consisting of a continuous-current generator driven by a suitable alternating-current motor. For other classes of work the generator may be of the alternating-current type, or the motor may be wound for continuous current; or both motor and generator may be of the same type. Such an apparatus is called a motor generator.

The two elements, motor and generator, are usually coupled mechanically together and mounted on a common bed-plate. In alternating-current work either a synchronous or an induction motor may be employed for the motor element. The modern tendency in large units is toward synchronous motors, both because of their advantage in the matter of phase control and because they can be more readily wound for high-voltage supply circuits.

* See chapter on Rotary Converters.

Motor Generators Supplying Continuous Current. — Where the motor element in a set delivering continuous current is of the synchronous type, the necessary field excitation may be supplied from the direct-current generator, provided the voltage of this is not too high (see remarks on excitation potential on page 27); otherwise the field circuit is supplied from an independent exciter, which is frequently direct connected. Starting and syn-

Fig. 126.

chronizing of synchronous sets is effected by the same methods as have been described in Chapter VI. for synchronous motors; or where a direct-current supply is available either from other sets in operation or from a storage battery, the motor-generator set may be started from the direct-current end, using the generator element as a motor. The general appearance of a two-unit set, consisting of continuous-current generator, synchronous motor and direct-connected starting motor, is shown in Fig. 126. This set has a normal output of 400 kilowatts at 600 volts

on the continuous-current side, and embodies the standard construction of the Westinghouse Company.

A motor generator built by the Allgemeine Company is illustrated in Fig. 127. The driving motor is of the induction type, and the direct-connected exciter provides a variable excitation to the continuous-current generator, which works on the Ward-Leonard system. This is the

Fig. 127.

type of motor generator used in the Ilgner system, the fly wheel (not shown in the cut) being carried in separate bearings at the motor end of the set.

The advantage of the motor generator over the rotary converter lies principally in the fact that the voltage on the continuous-current end is independent of voltage fluctuations on the alternating-current end. The motor and generator windings being electrically distinct, the generator voltage for a given condition of load and excitation depends

only on the speed, which is not affected by changes in the alternating voltage except to a limited extent where the motor is of the induction type. The generator may be compounded for automatic voltage regulation to a degree that would not be feasible in a rotary converter. A further advantage, where the driving motor is of the synchronous type, is the possibility of greater compensation by phase control for lagging current on other parts of the system. The motor may also be wound direct for line potential where this is not too high, thus saving the cost of step-down transformers. The motor generator is especially useful on circuits of 60 cycles and over, particularly in large capacities where the design of a rotary converter might be difficult.

As an offset to these advantages the motor generator is inferior in efficiency, higher in cost, and usually requires more floor space. Taking the efficiency of the motor and generator at 93 and 92 per cent respectively, the total efficiency of conversion is 85.6 per cent. The conversion efficiency with a rotary converter of equal output, including the transformers that are usually required, would be the product of converter efficiency, say 94 per cent, and of transformer efficiency, say 97.5 per cent, or 91.7 per cent over all, showing a better performance by about 6 per cent. From the standpoint of first cost, and assuming the same speed in both cases, the rotary converter with its transformers will require the smaller investment; for even if the cost of the generator is considered to be balanced by that of the converter, it is obvious that the cost of the motor will exceed that of the transformers. The difference is lessened when the motor-generator set can be designed for a higher speed than the rotary converter. The saving

by the use of three-phase transformers for the converter may offset this gain. The net difference generally will be found to be from 10 to 30 per cent or more against the motor generator.

In the matter of floor space the difference need not be very marked if the motor generator is of high speed, and if reference is had not merely to the net but to the gross floor space, by which is meant the actual ground area covered by the apparatus, plus an allowance for the necessary passageways.

Rotary converters, which were first developed in America, have enjoyed a wider use in this country than in Europe, where the motor generator is more generally employed. Experience has shown that each type has its own peculiar advantages, and a greater discrimination than formerly is now being exercised by engineers in making a choice between the two.

Motor Generators as Frequency Changers. — In alternating-current plants employing a low frequency, there is sometimes a need for a limited amount of current of a higher frequency. For instance, a supply of current for incandescent or arc lighting may be required from an installation where the frequency is 25 cycles. To meet such cases a frequency of 60 cycles, or any other periodicity suitable for lighting, may be obtained from a motor-generator set in which a generator of the desired output and frequency is driven by a motor taking its supply from the low-frequency circuit. In such cases the motor is usually of the synchronous type, which insures uniform frequency in the generator independent of load fluctuations, and also makes it possible to operate the motor generator in the reverse sense, i.e., taking power from the

high-frequency mains and delivering energy at the low frequency. This feature is valuable in the not uncommon case where such frequency-changing sets are used to tie together two separate systems of different frequency which may supply the same or adjacent territory.

Since the two machines constituting the frequency-changing set are mechanically coupled, the speed for which the set is designed must be one which will give correct frequency in both motor and generator elements simultaneously, having regard to the number of poles with which each member is provided. Where the ratio of the higher to the lower frequency is a whole number, as in a set transforming from 25 to 50 cycles, this requirement is easily fulfilled. In the case assumed, the generator would have twice as many poles as the motor, and the set could be designed for any speed which would suit the motor, according to the equation

$$\text{Speed} = \frac{120 \times \text{Frequency}}{\text{No. of poles}}.$$

The choice of speed is more restricted where the ratio of frequencies is not a simple number. Taking the case of a conversion from 25 to 60 cycles, the possible speeds for the 25-cycle motor are as follows:

Motor, 25 Cycles.

Poles	Speed
2	1500
4	750
6	500
8	375
10	300

etc.

The speeds nearest to the above values and corresponding to a frequency of 60 cycles are:

60 Cycle Generator.

Poles	Speed
6	1200
10	720
14	514
18	400
20	360
24	300

etc.

Considerations of first cost point to the choice of a high-speed design, yet in this case the highest available speed that is common to both frequencies is 300 revolutions, a speed which is very low for self-contained apparatus of this description. Where it is unnecessary to preserve the exact ratio of frequency, a compromise can be effected, as by selecting a four-pole design for the motor giving a speed of 750 revolutions and a delivered frequency of 62.5 cycles with a ten-pole generator.

In the parallel operation of frequency-changing sets an equal division of load cannot be secured unless the relative angular position of the rotating elements of motor and generator respectively is the same in each set. If in one set the angular position of the generator is leading with reference to that of the other machines, it will take more than its share of load, and vice versa if lagging. Accurate machine work is therefore necessary in fixing on the shaft the relative angular position of the two revolving elements of the set, although even with the utmost care it is not possible to locate these parts with absolute accuracy. The equivalent result is secured in machines of recent

manufacture by so arranging the stationary element of one of the two machines that it can be given a small angular shift. This scheme is embodied in the frequency-changing set shown in Fig. 128, which is one of 500 kilowatts capacity converting from 25 cycles at 13,000 volts to 62.5 cycles at 4000 volts. The circular structure constituting the stationary armature of the generator is carried in a cradle formed by the two supporting feet. By the two vertical

Fig. 128.

set screws seen on the outside of the frame the necessary angular adjustment is made, after which the frame is clamped in place. The adjustment may be made on the motor with the same result.

Induction Type Frequency Changer. — In another type of apparatus for changing the frequency, the generator element is substantially like an induction motor with polar-wound armature, the armature being rotated by a syn-

chronous motor in a direction, for increase of frequency, opposite to that in which it would naturally tend to revolve. The low-frequency current is fed to the primary or field, and the high-frequency current is taken from the secondary or armature by means of collector rings. The frequency of the output will depend on the speed and direction of rotation of the secondary and on the number of poles for which the primary is wound.

If N_1 = natural speed corresponding to number of poles in primary at the frequency impressed,

and if N_2 = forced speed of rotation, N_2 being negative for rotation in the natural sense and positive for rotation in the opposite sense, the frequency delivered by the secondary will be

$$\text{Secondary Frequency} = \frac{N_1 + N_2}{N_1} \times \text{Primary Frequency}.$$

Thus, if the secondary is run at natural speed but in opposition to its natural direction of rotation, the secondary frequency will be double that of the primary. If run at half natural speed in the natural direction, the secondary frequency will be half the primary.

To convert from 40 to 60 cycles, we could use a four-pole generator element, and drive the secondary at 600 revolutions per minute against the natural direction by means of an eight-pole motor. The natural speed of the secondary would be 1200 revolutions. By driving it in the opposite direction at a speed of 600 revolutions, the number of alternations will be that due to an equivalent

speed of 1800 revolutions in a four-pole field, or 60 cycles. Or, by the above formula,

$$40 \times \frac{1200+600}{1200} = 60 \text{ cycles.}$$

The capacity of the driving motor bears the same proportion to the total output that the increase in frequency bears to the final frequency. In the generator element the capacity of the secondary must equal the output. The capacity of the primary has the same proportion to the total output that the initial frequency bears to the final frequency. As an illustration, the above frequency changer when intended to deliver an output of 100 kilowatts would be made up as follows, neglecting losses:

Generator Element.

Capacity of secondary $= 100$ K.W.

Capacity of primary $\frac{40}{60} \times 100 =$ 66.6 K.W.

Motor Element.

Capacity $\frac{20}{60} \times 100 =$ 33.3 K.W.

For a given amount of energy transformed, this type requires a minimum of capacity in the transforming unit. This saving is largely offset by certain disadvantages, among which are the interdependence of the windings, which causes voltage fluctuations on the primary to reappear equally in the secondary; the absence of any

simple means for controlling the voltage of the secondary; and the difficulty of winding the generator for high voltage, either on armature or field. These have caused this type of machine to be practically superseded by the motor generator.

Motor Converter. — This device, in its design and operation, partakes of the characteristics both of the rotary converter and the motor generator, and in external appearance is not essentially different from the latter.

The motor converter consists of two elements, an induc-

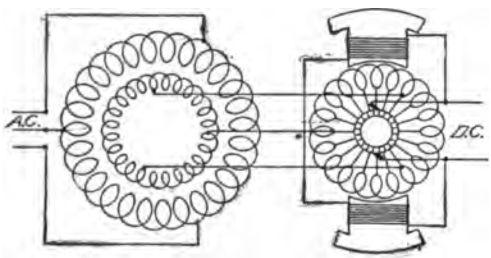


Fig. 129.

tion motor and a rotary converter, which are mechanically coupled, and which are also electrically coupled by permanently connecting the rotor of the motor to the armature of the converter, as shown on the accompanying diagram of a three-phase, bipolar unit (see Fig. 129). By this arrangement the power is transmitted through the induction motor element of the machine, partly mechanically and partly electrically, to the converter element. Inasmuch as the motor and converter are connected in concatenation, the synchronous speed is divided, so to speak, between these two elements in the ratio of the number of poles of the converter element to the total number of

poles of both alternating-current and continuous-current elements. The actual shaft speed, therefore, must be that corresponding to the synchronous speed for the sum of the number of poles on both machines, and hence much lower than the speed of an ordinary rotary converter designed for the same frequency. For instance, if the two elements have an equal number of poles — six poles on the induction motor and six poles on the converter — the actual speed of the machine will be one-half of the synchronous speed of an ordinary six-pole rotary converter supplied from the same alternating-current line.

Since the continuous-current armature of the motor converter operates partly as a rotary converter armature and partly as the armature of a continuous-current generator, the I^2R loss in the armature conductors and the field loss due to armature reaction will have values lying between the corresponding losses in a rotary converter and in a continuous-current generator. The efficiencies will therefore be somewhat higher than for the generator of the same capacity in a motor-generator set and lower than for a rotary converter.

Where the alternating voltage is not too high, the motor element may be wound direct for line potential without step-down transformers, thereby effecting some saving in space and cost on the complete outfit. Moreover, the motor converter does not require any reactance for compounding, as there is enough reactance for this purpose in the induction motor. Another advantage resides in the fact that main slip rings are done away with, the alternating-current rotor and the continuous-current armature being simply connected together along the shaft.

One of the chief advantages of the motor converter for

the higher frequencies is that a much lower frequency is impressed on the converter armature than is supplied from the line to the induction motor. This feature means a converter element with a comparatively small number of poles, and correspondingly small number of sets of brushes and low peripheral speed of commutator, resulting in low maintenance and good commutation characteristics. Since the dimensions of the induction motor element depend largely upon the primary frequency and not upon the speed of the rotor, considerable weight economy will be effected in motor converters for the higher frequencies, as compared with the motor generator.

The motor converter is readily started from the alternating-current side by the methods customary with induction motors of the resistance-in-armature type. In parallel operation, voltage control and other characteristics, the behavior of the machine is analogous to that of a rotary converter with considerable reactance in circuit. The motor converter, being a synchronous piece of apparatus, is subject to the same troubles from hunting as those to which rotary converters are liable, and from the same causes, — which may be treated by the expedients employed in the case of synchronous apparatus generally.

Synchronous Rectifier. — A rectifier is a device for changing an alternating current into a continuous current, without the aid of rotation in a magnetic field. In the single-phase synchronous rectifier a two-part commutator is revolved in synchronism with the alternating-current supply, the two halves of the commutator being permanently connected to the supply circuit. Two opposite brushes bearing on this commutator will therefore receive current that is unidirectional though pulsating. Polyphase

synchronous rectifiers are constructed on similar principles. Excessive sparking marks the operation of practically all synchronous rectifiers unless the rectified current is of very small value. They have therefore found only a restricted application, and have not been successfully built for an output of more than a few amperes.

Mercury Rectifier. — In this device, which embodies no moving parts, application is made of that property possessed by ionized mercury vapor of being a conductor to current of one polarity only. The rectifier proper consists of an exhausted glass vessel or tube of approximately pear-shaped form (Fig. 130). Sealed into it are four terminals, the cathode, *B*, the two anodes, *AA*, and the starting anode, *C*. The two anodes are connected across the alternating supply, and each thus becomes alternately positive and negative during the successive cycles. The cathode, located at the bottom of the tube, is covered with mercury, from which is liberated the ionized vapor on whose properties as a conductor to currents of one polarity the working of the device depends. When either anode is positive, the mercury vapor within the tube permits an arc to be formed between that anode and the cathode, which is negative. When the polarity of the alternating current reverses, the other anode becomes positive, and the arc now passes from the second anode to the cathode, which is still negative, no current flowing from the first anode,

Fig. 130.

since its polarity is now such that any current flow would be in a direction opposite to that in which the mercury vapor will act as a conductor. Hence, during the complete cycle the cathode is continuously negative, and the current at this point is unidirectional. Each anode passes current during half the wave, the first anode during the first half and the second anode during the second half. The use of the entire wave is shown by the oscillograph records in Fig. 131. The upper curve shows the current from one

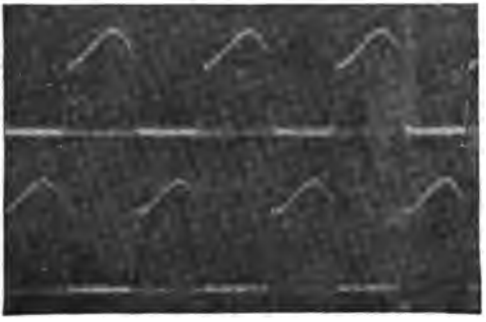


Fig. 131.

anode, and the lower curve the simultaneous current from the other.

If it were possible to maintain the arc on a single-phase rectifier without auxiliary apparatus, the resulting wave of continuous current would be a pulsating wave of the same characteristics as the alternating-current wave, the negative portions of the alternating-current wave appearing reversed in reference to the zero line. A wave shape of this form reaching a zero value twice in every cycle cannot exist, because if the current falls to zero for even an infinitesimally short time, the cathode will cease to give off

ionized vapor and the arc will be extinguished. Suitable reactances are therefore provided, of which the discharge voltage is sufficient to maintain the arc during the period when the alternating current is passing through zero. These reactances also serve to smooth out the current pulsations in the continuous-current side so that the current at the cathode is not only unidirectional but one with pulsations of commercially negligible amplitude.

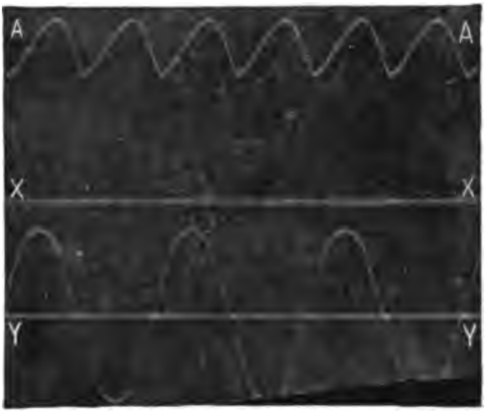


Fig. 132.

The resulting direct-current wave formed is shown at *AA* in Fig. 132 with reference to its zero line *X X*. Curve *AA* is obtained by superimposing the two curves shown in Fig. 131. In Fig. 132 the wave of simultaneous impressed alternating *E.M.F.* is shown at the bottom with reference to its zero line *Y Y*.

The action of the reactances is seen from Fig. 133, the upper curve showing the charge and discharge voltage of the reactance due to the impressed alternating *E.M.F.*

shown by the lower curve. In the upper curve the discharge voltage, which is that value below the zero line XX, is seen to occupy considerably more than half the cycle. It is this overlap which eliminates the zero points mentioned and prevents the arc from being extinguished.

Referring to the diagram of connections (Fig. 134) the cathode B forms one terminal of the continuous-current circuit. The other terminal is at the junction D, between

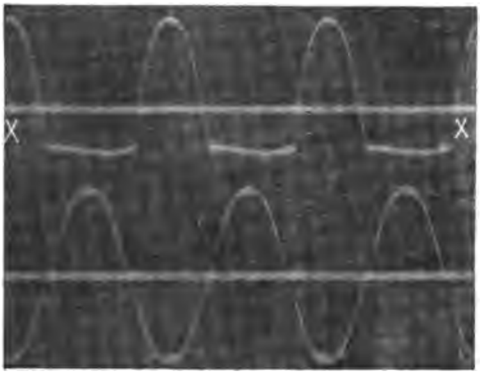


Fig. 133.

the two reactive coils E and F. The load J is indicated as a storage battery which is being charged. Assuming an instant when the terminal H of the alternating-current supply is positive, the anode A is positive, and the current-carrying arc flows from A to B. Following the direction of the arrows, the current passes through the external load J, through the reactance E and back to the negative alternating-current terminal G. A little later when the $E.M.F.$ impressed on A falls below the value sufficient to maintain the arc against the counter $E.M.F.$ of the arc

and the load, the reactance E, which has heretofore been charging, now discharges, the discharge current being in the same direction as the previous charging current. The discharge voltage of E serves to sustain the arc in the rectifier until the *E.M.F.* of the alternating supply passes through zero, reverses and builds up again to a value that makes A' sufficiently positive to start an arc between A' and B. The discharge circuit of the reactance E is now through the arc $A'B$, and the current flowing between A' and B in the rectifier is due in part to that supplied by the reactance E and in part to that emanating from the terminal G, which has now become positive. The new circuit from the transformer is indicated by the arrows inclosed in circles.

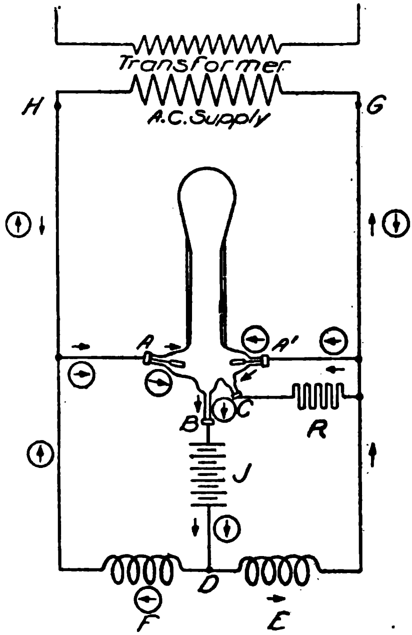


Fig. 134.

The initial ionization of the mercury vapor is accomplished by the starting anode C, which is brought into contact with the cathode by tilting the tube and allowing the mercury to bridge across the terminals B and C. The breaking of this mercury bridge when the tube is restored

to a vertical position starts a small initial arc which excites the cathode, and this causes the liberation of sufficient ionized vapor to enable the main anodes to become active. A small resistance, *R*, connected in series with the starting anode, limits the flow of current during starting.

The action of the rectifier tube is practically independent of frequency. The reactances used with it should, for best results, be designed for a frequency near that on which the device is to be used. Mercury rectifiers are adapted for use on circuits of a very wide range of voltage. While most commonly used on constant potential circuits of one or two hundred volts, they are equally adapted for higher potentials, and in special designs have been successfully employed to deliver continuous current at a pressure as high as 6000 volts in connection with constant-current series arc-lighting systems. The ratio of the continuous to the alternating-current voltage is slightly less than 0.5 and is practically constant at all loads and voltages, the ratio decreasing somewhat as the load increases, due to the voltage drop in the windings of the reactance.

A distinctive feature of the rectifier is the practically constant drop of approximately 14 volts in the arc itself. This drop is not in the nature of a loss of power in resistance, but is a counter *E.M.F.* which does not change with load, frequency or delivered voltage.

Neglecting losses in the reactance, it is therefore seen that the efficiency of the rectifier will be higher on high-voltage than on low-voltage circuits, for the percentage of power used in overcoming the counter *E.M.F.*, which has always the constant value of 14 volts, is small when the delivered voltage is high. For example, the efficiency, including reactance losses, of a rectifier delivering a con-

tinuous current of 30 amperes at 80 volts will be above 75 per cent at all loads from quarter load to full load. With the same output at a potential of 110 volts the efficiency will be increased to 80 per cent. These efficiencies are very striking compared with those obtainable from a motor-generator set of equivalent output, from which in so small a unit it would be difficult to obtain more than 70 per cent even at full load, while the quarter-load efficiency would be hardly better than 40 per cent.

The power factor averages about 90 per cent over considerable ranges of load. This value is also materially higher than could readily be attained by an induction motor generator set of the same capacity.

The ampere capacity for which mercury rectifiers have thus far been successfully built appears limited to about 40 amperes. Where the conditions require a larger output than can be supplied from a single apparatus, parallel operation is satisfactorily effected.

CHAPTER X.

SWITCHBOARDS AND STATION EQUIPMENT.

Control of Alternating-Current Apparatus. — The rapid introduction of generators of extremely large output, and the use of currents of increasingly high pressures, have demanded a corresponding advance in the development of all details of alternating-current switchboard equipment. Under modern conditions large districts are often dependent upon a single generating station for the supply of current for lighting or for power. In such cases even a temporary interruption of the supply is most serious, and elaborate precautions are taken to insure continuity of the service.

The successful operation of modern alternating-current distribution systems is due primarily to the perfection of the oil switch and circuit breaker, which will be described below. Protection against short circuits within the station is secured by a liberal spacing and careful insulation of the conductors. In large plants, especially those working at high voltage, all conductors of opposite polarity are separated by masonry barriers, or located in fire-proof compartments. This construction is used especially for the bus bars, but is applied also to the machine, transformer and feeder circuits. In this way the effects of a short circuit are localized as far as possible so that the operation of other circuits shall remain unaffected. All these provisions for the proper running and spacing of the

wiring, and for the convenient location of the various devices which constitute the modern alternating-current switchboard installation, require that the station building shall be designed with a full knowledge of the switching equipment which it is to contain.

Switches and Circuit Breakers. — Before the development of the present effective devices the switching of alternating-current circuits was done with knife-blade switches similar to those familiar in continuous-current work, the principal difference lying in the increased length of blade so as to give a greater breaking distance suited to the higher voltages. Switches of this type for use on circuits as high as 25,000 volts have been constructed with switch blades five to six feet long. These switches require a great amount of room on account of the sweep of the long arms. When opened under load vicious arcing frequently follows, and the arc may hold persistently, the heated vapors serving to maintain a path of conductivity through the air. Thus under severe conditions a switch of this type, even though of exaggerated dimensions, may be unable to open the circuit. A further and most important disadvantage is that even though such an arc may ultimately extinguish itself, a phenomenon of rise of potential may be produced when interruption of the circuit takes place. This is often sufficient to break down the insulation of such apparatus as is connected to the circuit. It was soon recognized that to meet the new conditions some other procedure was necessary than merely to enlarge the dimensions, without modifying the type, of a switch that was satisfactory under earlier and less difficult requirements. Among the various types devised none were fo nd to meet adequately the increasingly severe conditions until

the advent of the oil switch. For practically all alternating-current work this type is now used to the exclusion of all others.

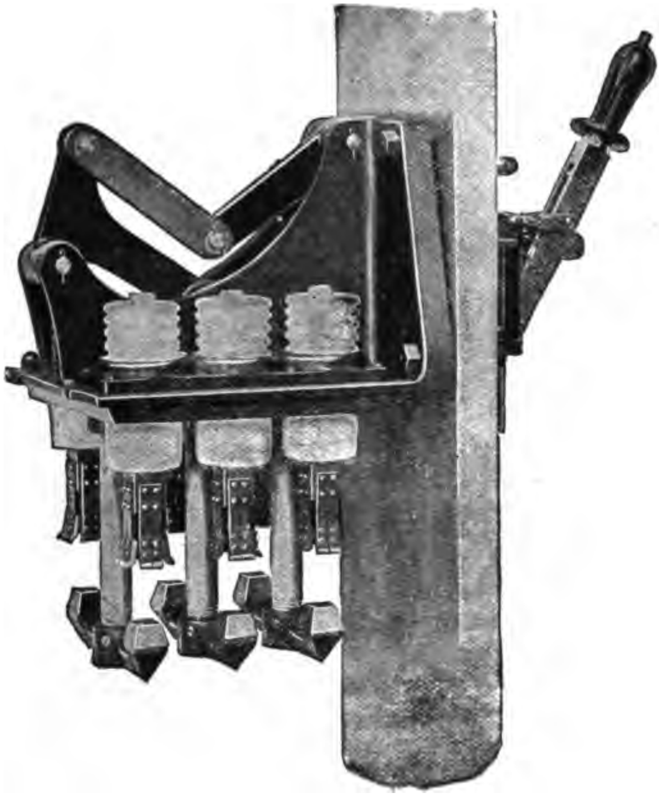


Fig. 135.

The switch in its simplest form consists of one or more sets of contacts by which the circuit is made or broken beneath the surface of oil contained in a surrounding vessel.

A typical three-pole oil-break switch with oil tank remove is shown in Fig. 135. Connection between the opposite

clips of each pole is made by the bridging pieces seen at the bottom. These are connected to wooden rods which are raised and lowered simultaneously by a system of toggles and levers connected to the operating handle on the front of the board. Where the potential exceeds about 2,000 volts these switches, instead of being mounted on the back of the panel, are preferably mounted on a separate framework some distance away, so as to avoid crowding the wiring. When mounted in this way, connection between the switch and the operating handle is effected by a system of rods which are usually located below the floor line. Or the switch may be actuated electrically by means of a solenoid, the circuit of which runs to a small controlling switch on the front of the panel. This type is illustrated in Fig. 136. In this photograph separate compartments are seen to be provided for each pole. In this way more perfect insulation is secured and the rupturing capacity increased.

Fig. 136.

For stations of the largest capacities the oil switch is constructed so that each break of each phase is effected in a separate oil vessel. A two-phase switch of this form consists of four single-phase switches, each of which consists of two separate contacts each inclosed in its own oil

vessel. A three-phase switch consists of three such pairs of contacts. All the contacts of all the phases are arranged to be closed or opened simultaneously. The several

Fig. 137.

single-phase elements are separated by masonry barriers and surmounted by the operating mechanism.

The general arrangement of an electrically operated switch of this form assembled in its compartments is shown

in Fig. 137. The internal connections of a single element are shown in outline in Fig. 138. Each single-phase element consists of two metal cylinders which contain the oil and the contacts. The incoming lead is attached to one cylinder, and the outgoing lead of the same phase is attached to the other. Two copper rods, joined at the top by a metallic cross-head, slide through an insulating sleeve and make contact at the bottom of the cylinders.

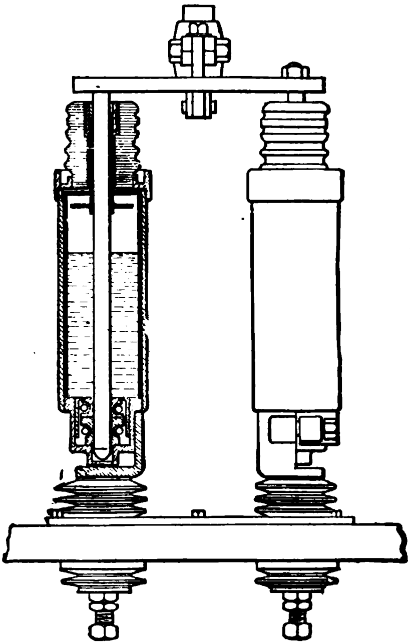


Fig. 138.

The switch illustrated in Fig. 137 is electrically operated by a small motor which drives a worm gear. This transmits motion to a rocker shaft through a friction clutch. Motion is communicated to the contact-making parts by means of wooden insulating rods actuated from the three arms which are keyed to the rocker shaft. At both ends of the stroke a spring is compressed by the action of the motor and held in such a way that if current is applied to the motor a few revolutions of its armature, requiring a fraction of a second, will release the spring and throw the

switch. The motor continues to revolve until it has compressed the other spring, and is then disconnected by means of an auxiliary contact on the operating mechanism. A second application of current to the motor will now release this spring and throw the switch back to the original position, after which the first spring is again compressed and the motor disconnected from circuit in the manner described. The circuit to the motor is led through a small controlling switch placed on the front of the switchboard panel. Suitable pilot lamps are provided, the respective circuits of which pass through contacts on the operating mechanism. These lamps become alight, one for the closed and one for the open position, and inform the attendant of the proper functioning of the switch, which may not be within his view.

The switch shown is designed for circuits up to 15,000 volts. It occupies a floor space 2 feet 7 inches by 4 feet 6 inches, and is 8 feet high over the top of the operating mechanism. The movement of the contact rods is 20 inches. When built for 60,000 volts the floor space is 5 feet 2 inches by 11 feet, the overall height is 11 feet 9 inches, and the rods have a travel of 34 inches.

Switches of this general form are also made electrically operated by means of solenoids, or they may be operated by compressed air.

The superiority of the oil switch over all other types thus far introduced, lies in two features which are of nearly equal importance. These are its ability to interrupt the circuit with great certainty, and the fact that practically no rise of potential ensues when the circuit is broken. The effective action of the switch in interrupting the circuit is due to the cooling action which the oil has on the arc,

and which extinguishes it promptly by lowering the temperature below the value at which the arc can hold. The absence of any appreciable rise of voltage when the circuit is broken follows from the fact that in this type of switch the arc is broken at or near the zero point of the wave.

Whenever an alternating-current circuit is interrupted there is a definite amount of electromagnetic and electrostatic energy stored in the line which must be spent in some way. The magnitude of this energy depends on the inductance and capacity of the circuit and on the instantaneous value which the current has at the moment of interruption. The circuit being interrupted, the only path that can be taken by the current which was previously flowing through the switch is now formed by the line capacity, and the line therefore becomes charged to a certain potential depending on the line constants, this potential being proportionate to the value of the current at the moment of interruption. In the air switch interruption is liable to take place at the maximum of the current wave, and a very high voltage may thus result. If, on the other hand, the current is interrupted when at zero value, no rise of potential will occur. This is what takes place in the oil switch and constitutes a feature of the highest value. This, together with the safety and general effectiveness of the device, marks the oil switch as one of the most important developments of recent years.

Oil for use in these switches should be carefully selected. The requirements are in general the same as should be demanded for oil used in transformers of equivalent potential. A renewal of the oil is necessary from time to time, since its properties suffer deterioration through the gradual carbonizing effect produced by the arcing between the

contacts. No general rule can be given covering the interval between renewals, as this will depend on the number of times the switch is operated and on the severity of the load which it interrupts. In general, new oil is seldom required oftener than once in three months, and it is frequently found that even after a year's service the oil is still sufficiently good.

The various types of switches described above may be equipped with a tripping device to cause them to open automatically under given conditions. Thus the switch may be made to open when the load increases to a predetermined value, its action in this respect then corresponding to that of the familiar direct-current circuit breaker. This overload device may be of a type that will cause the switch to trip immediately in case a given overload is reached, or it may be so arranged that a certain time will elapse before the switch will function. Thus the device may be so adjusted that the switch will not open unless the overload persists for, say, five seconds. This feature is useful in preventing too frequent tripping of the switches, such as during overloads of very brief duration which would not harm the apparatus connected to the circuit. It also tends to make it easier for the switch to break the current in the event of a severe short circuit, because the switch does not open till after the first heavy rush of current has passed. When constructed in this form the overload device is said to have the "definite time" feature. Another form is also used having what is called the "inverse time" feature. This takes its name from the fact that the time elapsing between the application of the overload and the tripping of the switch is inversely proportional, or nearly so, to the amount of overload. This type is used where

it is desired to have the switch open immediately in case of very heavy overload, while responding to the action of moderate overload only in case the duration of the excess current is considerable. If with either of these two types the overload is removed before the expiry of the time limit for which the device is set the switch will remain closed.

Fuses. — The use of the ordinary open fuse on high-potential circuits is in general subject to the same limitations and disadvantages as the air-break switch in respect to fire hazard, unreliability and dangerous rise of potential. Automatic oil switches have therefore been preferably employed for all important work. In new designs lately developed the fuse blows in a confined space of such a form as to cause the arc to be extinguished at the zero point of the wave, as in the oil switch. Fuses of satisfactory type should find a wide application in situations where moderate powers are dealt with under conditions which from the commercial standpoint would not permit the use of the much more costly oil switch.

Switchboards. — The modern alternating-current switchboard, especially for large powers and high voltages, is really an installation in itself, consisting of many separately located parts. The type and size of the oil switches, the space demanded by the bus-bar structure, and the necessary provision of liberal room for all high-tension parts, not to mention the space taken up by the switchboard panels themselves, require sometimes not less than one-quarter of the cubic contents of the station building for the accommodation of the switchboard equipment. Only a limited portion of the equipment can be mounted on the panels; the remainder must be disposed of elsewhere (see Figs. 147 and 148, which will be referred to later).

The panels may be either of marble or of slate. At 2,000 volts and less, live parts can safely be mounted on the panels if they are of marble. If of slate, they should carry no live parts at higher than 600 volts, the occasional metallic veins in this material rendering it inferior as an insulator. It is safer at even 2,000 volts, and almost imperative at higher voltages, so to arrange the circuits that the panels shall carry no live parts that are electrically in connection with the main circuits. This is accomplished by locating the switches and bus bars at a distance, and by connecting all measuring instruments on derived circuits fed from special instrument transformers. These are well-insulated transformers in which the primary is connected to the high-voltage circuit that is to be metered, the secondary leads going to the switchboard instruments. The frames of these transformers are grounded, as is also one side, or the neutral, of the secondary winding. Allowance for the ratio of transformation is made in the calibration of the instruments so that these may read directly in the units actually dealt with. By this means it is possible to keep within, say, 125 volts the potential of all wiring which must be carried to the panels; and since the manipulation of the main switches is effected either by means of an insulated system of levers, or electrically by means of currents at low pressure, all parts of the board with which the operator can come in contact are made perfectly safe. By this means also, slate panels become as satisfactory as marble, and have the advantage of more uniform appearance owing to their neutral tint, together with a slightly lower cost.

The panels are made of uniform height, and as far as possible of the same width, in order to present a symmetrical

appearance. They are arranged side by side and bolted to an iron framework. The measuring instruments are fastened to the front of the panel, the electrical connections for them being made behind the panel. On the front of the panel are also mounted the various switch handles and rheostat hand wheels within easy reach of the

Fig. 139.

operator. For large stations employing many electrically operated switches a compact arrangement of the operating board is often secured by grouping the various controlling switches on a sloping table or "bench-board" in front of the instrument panels. Such an arrangement is provided in the switchboard illustrated in Fig. 139. This switch-

board controls a large hydro-electric station having an output of nearly 50,000 horse power at 60,000 volts.

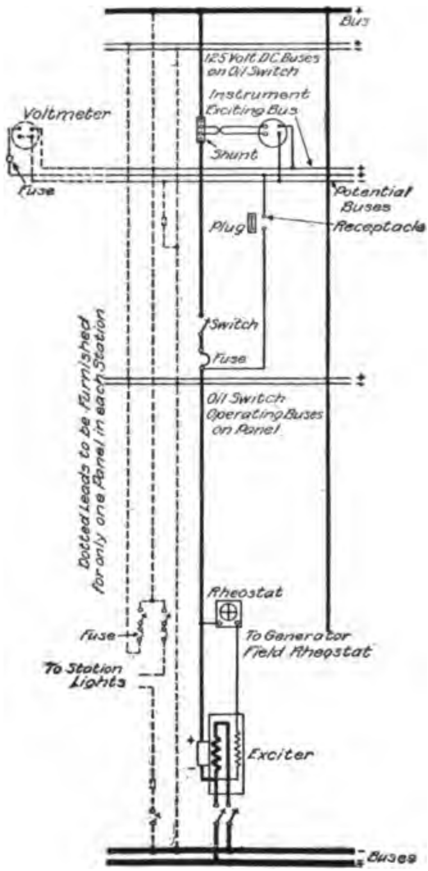


Fig. 140. Exciter Panel.

Typical Connection Diagrams. — The switchboard equipment in the average generating station will include

panels for the control of the generators, exciters, and outgoing lines, each machine and feeder having its own panel.

There are usually two exciter panels, as the exciters are desirably provided in duplicate, each of sufficient capacity to excite all the generators. The equipment of the exciter panels will include the necessary switches, field rheostat, and an ammeter. A single voltmeter will suffice for two or more exciters, the voltmeter being connected to any one at will by means of a small plug switch. The exciter panels may also be equipped with switches for the station lighting circuits where these are fed from the exciter generator. The general connections of the exciter panel are shown in Fig. 140.

On each generator panel, Fig. 141, the instrument equipment will include an ammeter, voltmeter, wattmeter, and the necessary synchronizing appliances. A power-factor meter is sometimes supplied, or the wattmeter may be made to indicate the wattless component of the output by means of a change of connections, thus serving the same purpose. Where an unbalanced load is anticipated, an ammeter is provided in each phase. In the diagram illustrated the generator is seen to be operated in conjunction with step-up transformers. These are tied directly to the generator terminals, and the switching is done on the high-tension side. With this arrangement each generator with its transformers is treated as a single high-tension unit. Where the transformer banks can be made to correspond in capacity and number with the generators, this method of control avoids the necessity for any low-tension bus bars, instruments, or switching equipment. The right-hand diagram of the figure applies where the main switch is

manually operated (as in Fig. 135). The left-hand diagram shows the arrangement used when the main switch

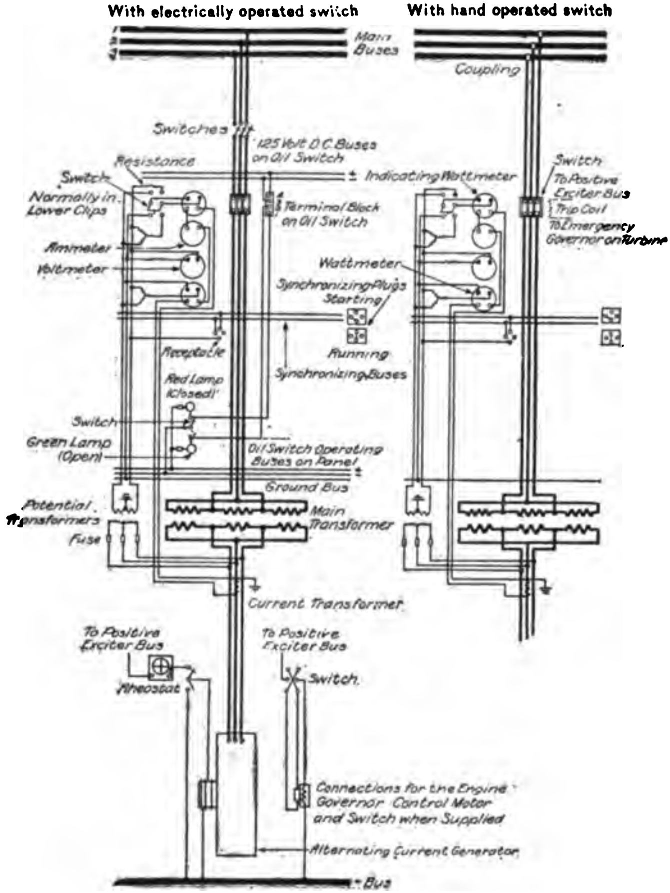


Fig. 141. Generator with Step-up Transformers.

is electrically operated, including the control switch and the connections of the red and green pilot lamps. Over-

loads on the system are relieved by the tripping of automatic switches in the feeder circuits. The generator switches are made non-automatic, since otherwise they also would trip out on overload, and delay in restoring power would ensue owing to the time required to resynchronize. In the diagram referred to the high-tension transformer switch may be regarded as the generator switch. The sketch shows the connections of the current and potential transformers for the instrument circuits, and shows that these are grounded, as previously mentioned.

Connections for a generator circuit where step-up transformers are not used are given in Fig. 41, on page 61. The same description applies to that figure as to the one just considered.

For the outgoing line, or high-tension feeder, the panel connections are given in Fig. 142, which, like the preceding, covers both the electrically operated and the hand-operated type of switch. The switch is arranged for automatic trip, generally on the definite-time principle. The tripping coils are usually actuated by current from the exciters, the tripping circuit being closed by a relay which in turn is actuated by current derived from a current transformer in the main circuit. An ammeter is provided for each phase, to give evidence of any unbalancing or of open circuits in any phase, as by grounding or breaking of one of the line wires.

Lightning arresters and choke coils are connected where the line leaves the building.

Coming now to the receiving or substation end of the transmission line, the arrangement for the control of the incoming lines is seen in Fig. 143. The connections and instruments are practically the same as for the outgoing

line, except that only one ammeter is usually needed. The switch is of the automatic type, so as to disconnect the sub-

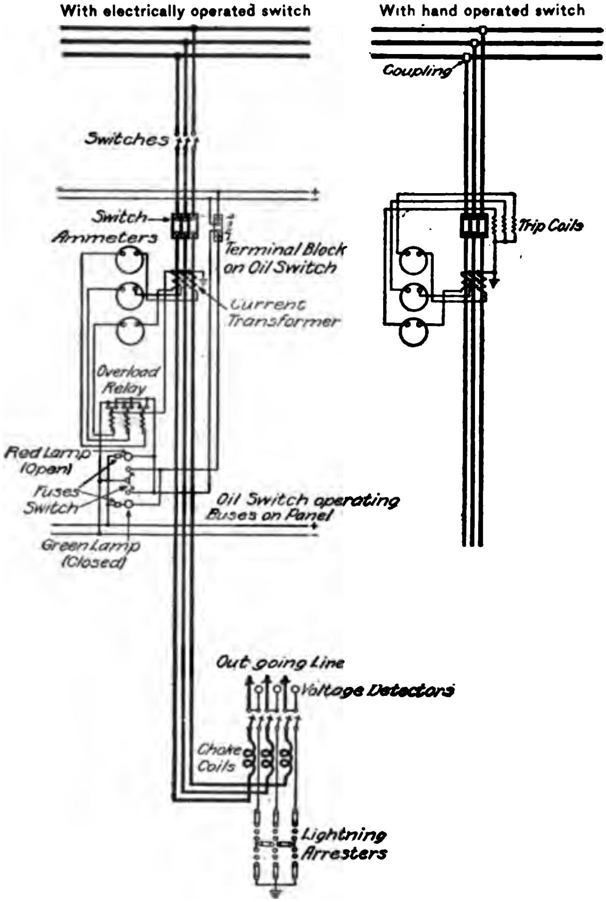


Fig. 142. Outgoing Line.

station from the source of power in the event of severe overloads or short circuits.

The details of the other substation panels will depend on the use to which the current is put, i.e., whether for

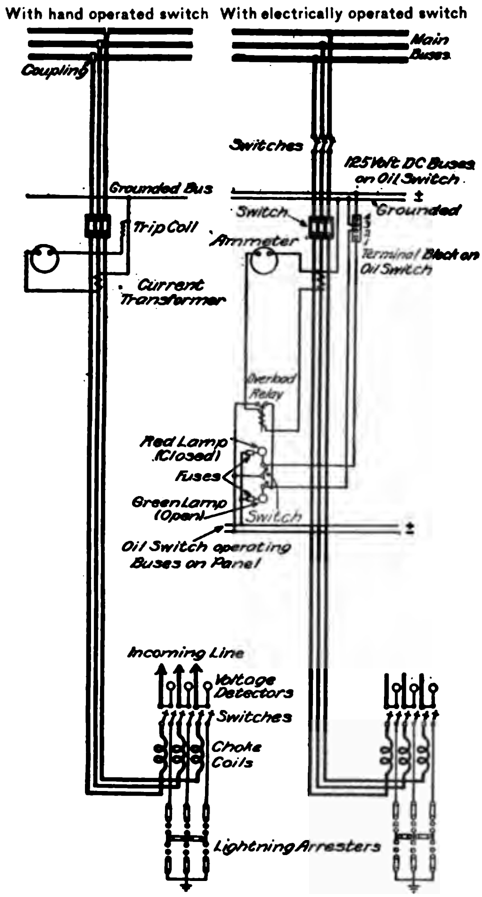


Fig. 143. Incoming Line.

lighting, power, or railway service. Assuming that the substation contains rotary converters supplying current

to a railway system, the machine connections are as shown in Fig. 144. In this figure the middle diagram applies

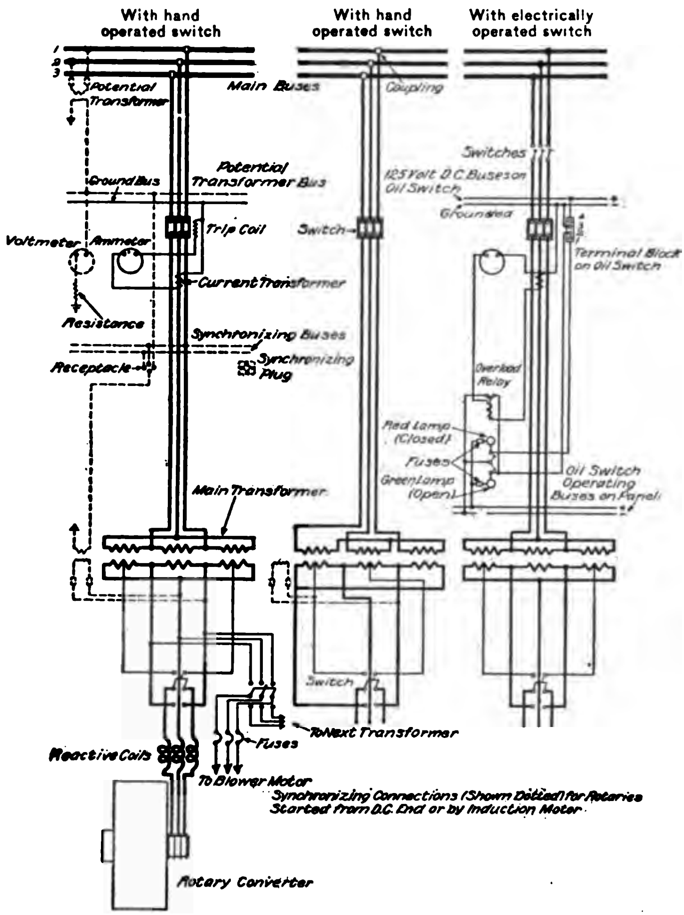


Fig. 144. Rotary Converter, Three-phase.

where the step-down transformers are connected star on the high-tension side, and the other two diagrams are for

the delta high-tension connection, the secondaries being delta in all three cases. The converter is three-phase,

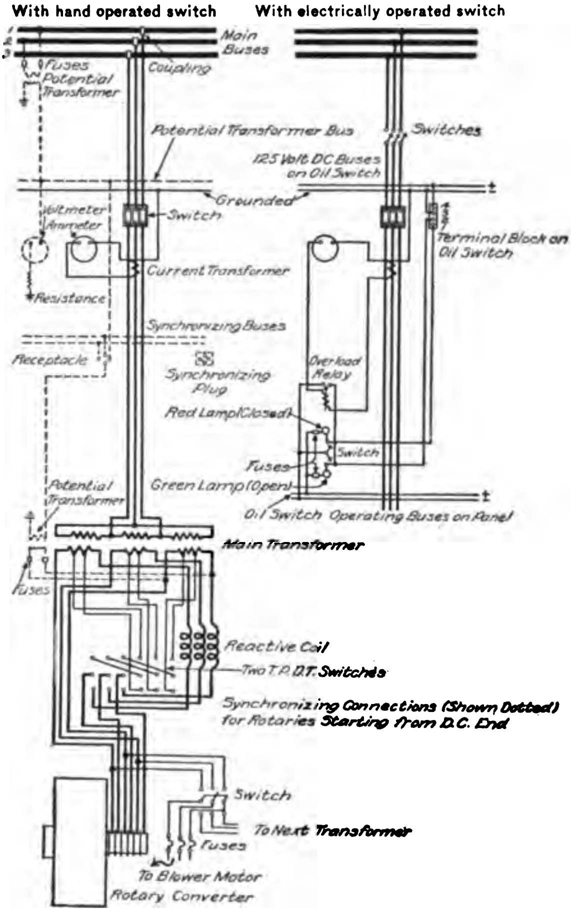


Fig. 145. Rotary Converter, Six-phase.

arranged to start from half voltage taps on the transformers (see page 218). Dotted lines show the connections which

have to be made for synchronizing when the converter is started from the direct-current end or by a starting motor. Each converter is fed from its own bank of transformers, and all switching on the alternating-current end, except for starting, is done on the high-tension side. For a six-phase converter the connections are given in Fig. 145, which differs from the preceding chiefly in the starting connections and in the connections of the transformer secondaries, which are diametrical.

On the continuous-current side of the converter the arrangements are shown in Fig. 146. An ammeter and recording wattmeter measure the output of each machine. A single voltmeter allows the voltage of any machine to be read by means of a plug switch. Small switches conveniently located control the lighting circuits of the substation. At the bottom of the diagram appear the connections of the shunt field with the switch for sectionalizing the winding when starting.

Location of Switchboard Equipment. — Reference has been made to the necessity of so arranging the design of the power house that sufficient room and a suitable location be provided for the switchboard equipment. This applies mainly to plants of large capacity or those working at high voltage, since in the case of small or low voltage plants the switches and bus bars may be mounted on the panels, permitting an arrangement that requires but moderate space. As an example of the former type, requiring an equipment of the most powerful switches and a spacious and fire-proof arrangement for the wiring, a typical station layout is shown in Figs. 147 and 148. These two cuts show the transverse section and plan of a water-power station now under construction, which will at the start generate 6,000 H.P. at

60,000 volts. The station building is being made large enough to accommodate additional generators in the

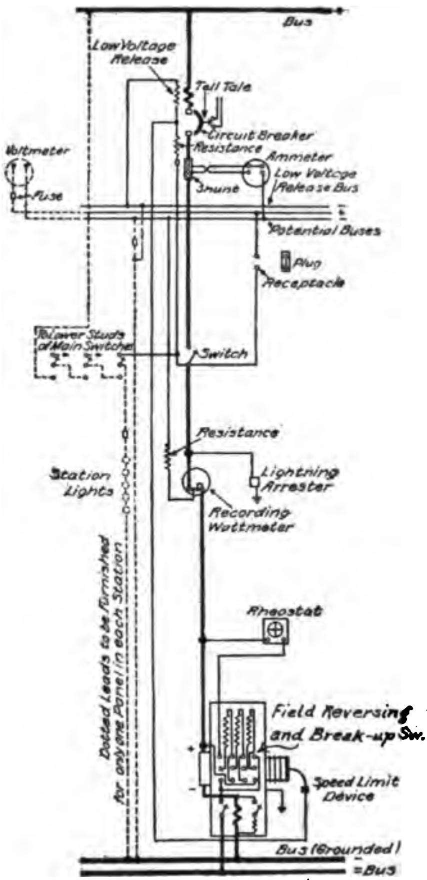


Fig. 146. Rotary Converter, D.C. End.

future sufficient practically to double the present capacity.

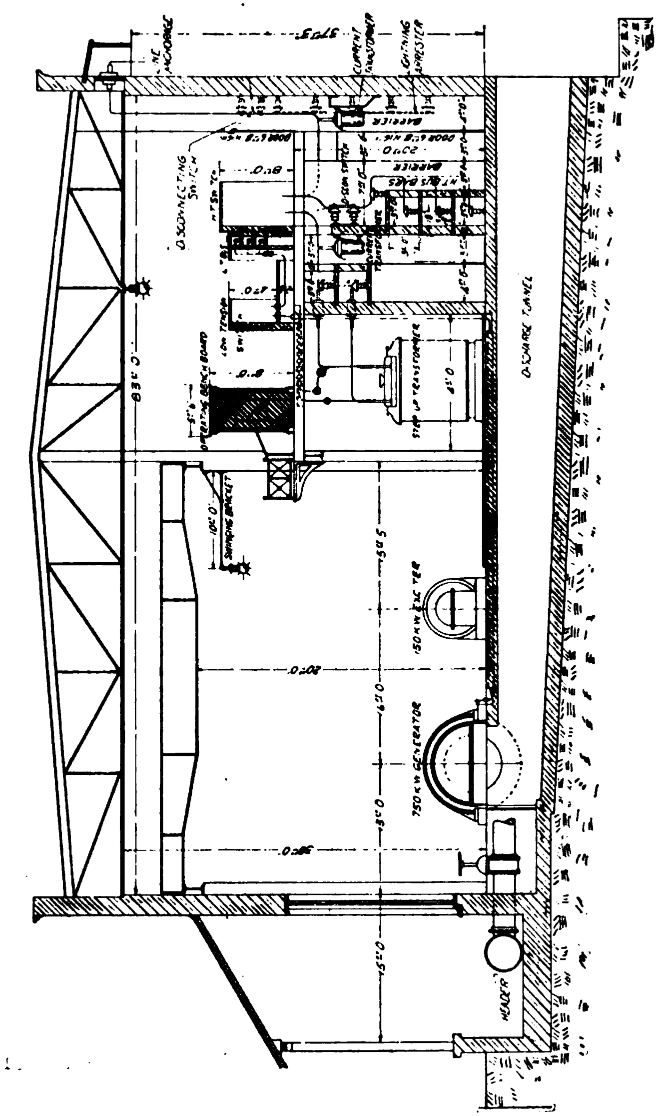

750 KW GENERATOR
150 KW EXCITER
STEP UP TRANSFORMER
OPERATING BENCH BOARD
DISCHARGE TUNNEL
HEADER
DISCONNECTING SWITCH
CURRENT TRANSFORMER
LIGHTNING ARRESTER
BARRIER
SWINGING BRACKET

Fig. 147.

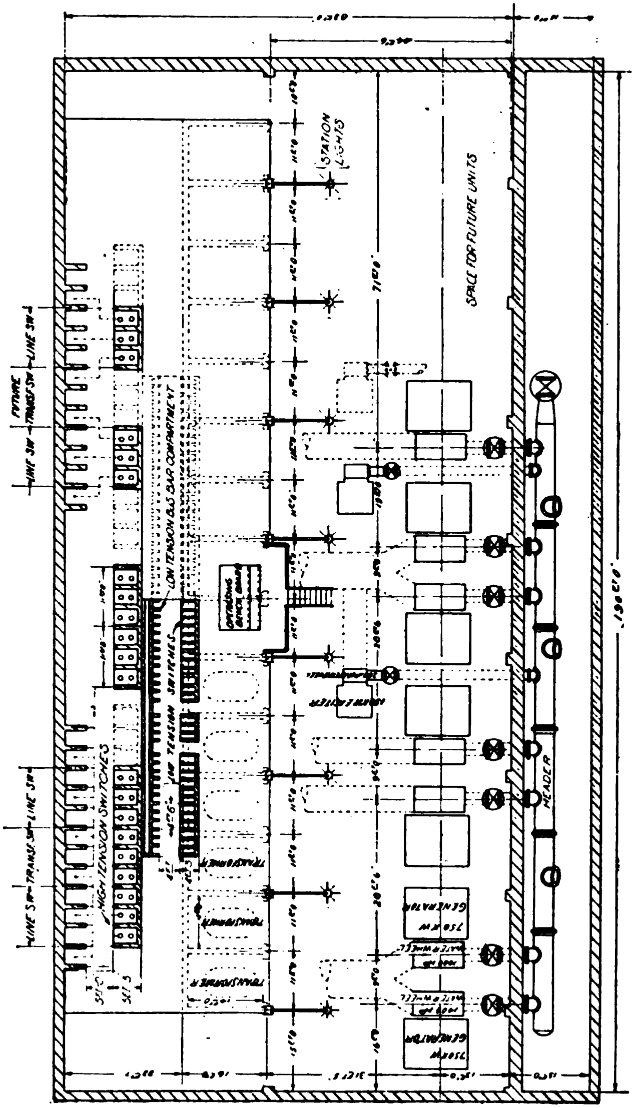

HIGH TENSION SWITCHES
LOW TENSION BUS BAR COMPARTMENT
LOW TENSION SWITCHES
SPACE FOR FUTURE UNITS
STATION LIGHTS
HEADER
750 KW GENERATOR
LINE SW
TRANSF SW
FUTURE

Fig. 148.

The operating bench board from which the station is controlled is located on a gallery from which an unobstructed view of the machine floor is obtained. Back of the operating board extend in two rows the switches for generator, transformer, and line circuits. Beneath the gallery are located the step-up transformers, each in a fire-proof com-

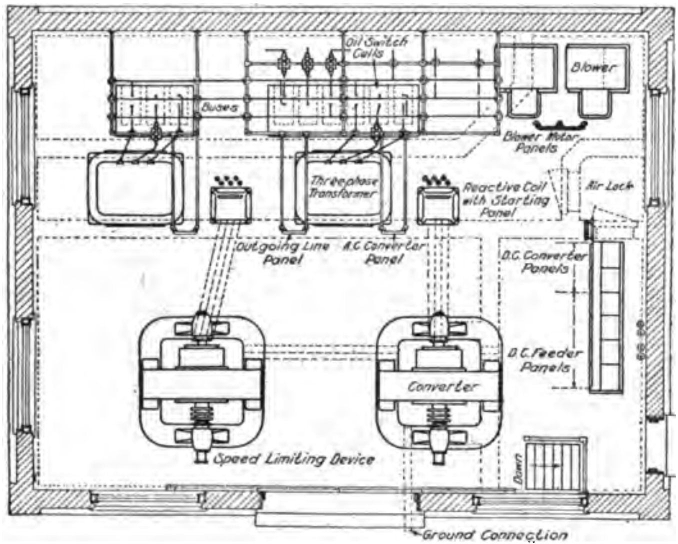


Fig. 149.

partment. The low-tension bus bars extend along the gallery behind the line of low-tension switches. The high-tension busses are located on the main floor beneath the high-tension switches. The leads from generators and exciters and from the low-tension side of the transformers consist of rubber-insulated, lead-covered cables carried in earthenware ducts. All connections of the high-tension

system are made with bare copper wire supported on insulators of the same type as are used on the transmission line. The location of the switches and other parts aims to provide the simplest and most direct layout for the connections between switchboard elements, a problem which in the

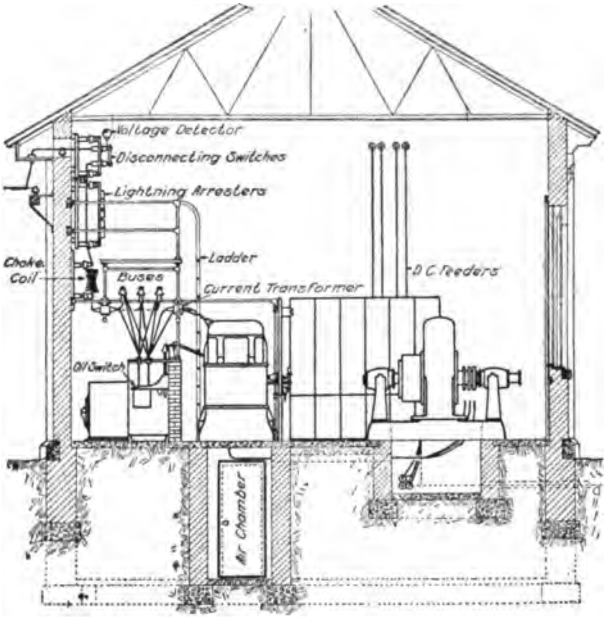


Fig. 150.

complexity of the modern plant is indeed a difficult one.

The arrangement of apparatus and of the switchboard equipment in a well-designed rotary converter substation for railway service is illustrated in Figs. 149 and 150. The high-tension current is stepped down by means of three-phase air-blast transformers, the location of which together with their blower sets is clearly shown.

Automatic Regulation of Potential. — Probably the most satisfactory device thus far introduced for the automatic regulation of generator potential is found in the Tirrill Regulator. This device controls the voltage of the generator by automatically changing the voltage of the exciter

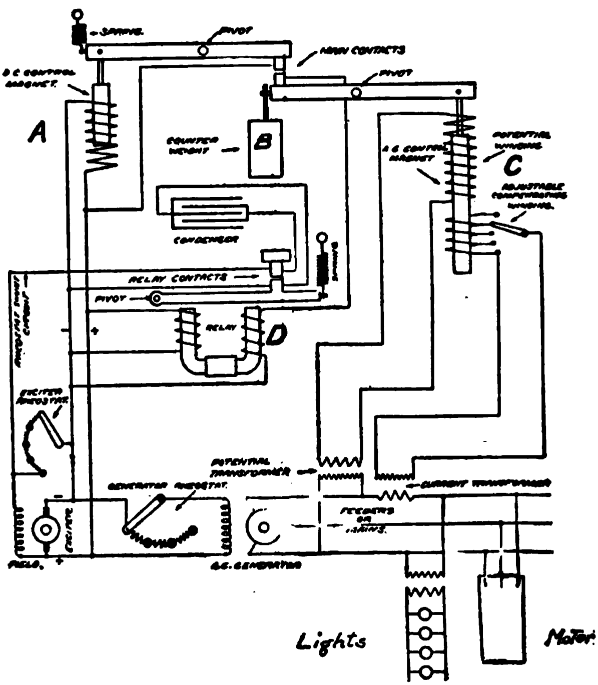


Fig. 151.

circuit and thus altering the excitation current of the alternator. The variation of the exciter voltage is effected by a set of contacts on the regulator which intermittently short circuit the rheostat in the shunt field of the exciter. Referring to the diagram of connections, Fig. 151, *C* is an

alternating-current magnet having a potential winding connected to the bus bars through a potential transformer. The core of this magnet is supported partly by the attraction of the potential winding and partly by the counterweight *B* at the opposite end of the pivoted lever. With an increase of load on the alternator the voltage tends to drop, and this lessens the current flowing through the potential winding of the magnet. The core will therefore fall and bring the main contacts together. An auxiliary circuit is thus established through the differential relay *D*, causing the relay contacts to close. These relay contacts are connected across the exciter rheostat, which is thus short-circuited. The exciter voltage, now vigorously augmented, brings up the alternator voltage till the increase of current through the magnet coil raises the core and separates the main contacts again. This acts in turn to separate the relay contacts and to put the exciter rheostat again in circuit, thereby preventing further rise of voltage.

In the action of the device the contacts are continually opening and closing with great rapidity, with the result that the exciter voltage is caused to assume such a value as will give the necessary excitation to the alternators for any condition of load. The device may be adjusted to give constant bus-bar voltage; or by means of a compensating winding, the effect of overcompounding may be secured. The appearance of the apparatus is shown in Fig. 152, the parts being lettered to correspond with the diagram.

Feeder Regulators. — In order to insure correct voltage at a number of different points fed from the same station, it is usually necessary to provide some means of controlling individually the potential of the separate feeders. This purpose is effected by devices known as pressure regulators,

or feeder regulators. They are made in several types, all being virtually one or another form of variable ratio transformer with the primary connected across, and the secondary in series with, the feeder to be regulated. The product

Fig. 152.

of the volts and amperes on the generator or bus-bar side is always equal to the product of the volts and amperes on the feeder side, minus the small loss in the regulator itself. This is shown, neglecting losses, by the diagram of Fig. 153, drawn for a single-phase regulator used on a circuit

of 100 amperes at 100 volts, the regulator having a capacity to raise (or lower) the voltage of the circuit by 10 per cent. In this figure the values are taken with the regulator in the maximum boosting position, while Fig. 154 shows the values corresponding to the position of maximum lowering effect.

In one form of regulator, the primary and secondary coils are wound on the same core, as in a transformer, and a number of taps are brought out from the secondary winding. These are connected to a dial switch, and the voltage variation is made by moving the switch to any desired contact. The connections of a single-phase regulator of this type are given in Fig. 155. When wound polyphase a similar arrangement is employed, consisting essentially of the use of as many single-phase regulators as there are phases. This form of regulator may be referred to as the switch type. It will be seen that there is a definite potential interval between the steps, which depends on the number of switch contacts.

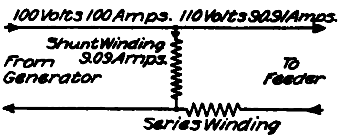


Fig. 153.

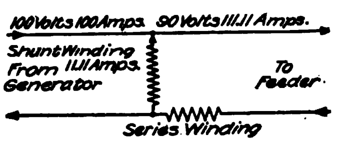


Fig. 154.

In another form of regulator constructed both for single-phase and for polyphase circuits, the two windings, primary and secondary, are each placed on separate circular and concentric slotted cores of laminated iron, one of which, called the stator, is stationary, and the other of which, termed the rotor, is arranged so that it may be angularly displaced with reference to the stator. This form of regu-

lator is known as the induction type, and has the important feature that it gives a perfectly smooth curve of potential change, as contrasted with the step by step change of the switch type, due to the fact that the potential generated changes with every alteration in the relative positions of stator and rotor. This is well illustrated by the curves in Fig. 156. From these curves it will also be seen that at no load the boosting and lowering effects are equal, while at

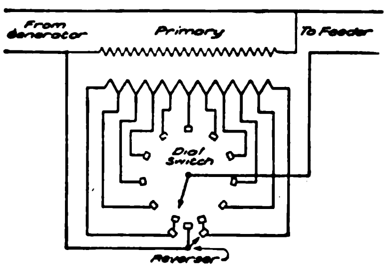


Fig. 155.

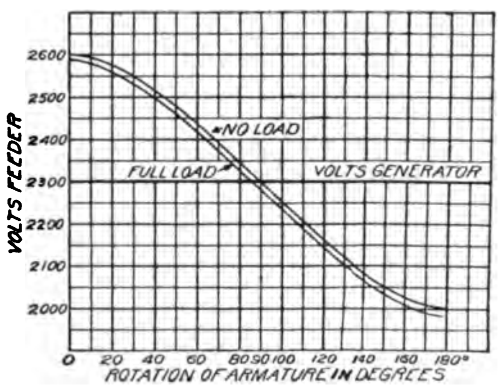


Fig. 156.

full load the lowering is always somewhat greater than the boosting for a given setting of the regulator. This is explained by the fact that the ohmic and reactive drop in the windings (which tends to make the regulator give a

lower voltage when loaded than when on open circuit) is additive when the regulator is lowering, and is subtractive when the regulator is boosting. This difference, in other words, is the analogue of regulation in a transformer. In the usual construction the secondary or series coil is wound on the inside circumference of the stationary core, and the primary or shunt coil is wound in the slots provided on the outside circumference of the movable core.

In the single-phase type the connections and arrangement of windings are given by Fig. 157. The primary, or rotor, contains two windings, — the active or shunt winding, connected across the line, and a second winding short-circuited on itself and arranged at right angles to the shunt winding, the purpose of the second winding being to decrease the reactance of the regulator.

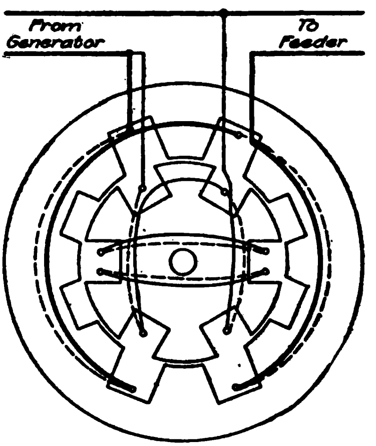


Fig. 157.

In the polyphase induction regulator the arrangement of parts and type of winding resemble closely the construction of an induction motor, as seen for example in Fig. 158, which illustrates the stator of a 25-kilowatt, three-phase regulator. Both primary and secondary have a definite polar winding embedded in slots on the inner and outer surfaces respectively of the stator and rotor. The flux

which generates the secondary voltage is rotative, as in an induction motor. It has a practically constant value, and hence generates in the secondary a voltage which is practically constant and which is independent of the relative angular displacement of the rotor. The variation of potential resulting from the action of the regulator, or, in other words, its ability to increase or decrease the voltage

Fig. 158.

of a circuit, depends on the fact that a change in the angular shift of the rotor produces a change in the phase displacement existing between the constant potential delivered to the regulator and the constant potential generated in its secondary, the magnitude of the resultant or delivered potential varying with the magnitude of this phase displacement.

This may be graphically illustrated, as in Fig. 159. Let *EO* represent the normal potential or bus-bar voltage of

one phase of the system, and let the radius *OB* represent the constant voltage induced in the secondary of the regulator. With the primary coil of phase 1, for example, directly opposite the secondary coil of the same phase, the voltage generated will be *OD*, opposed to the bus-bar voltage, and the regulator will lower by the maximum amount, making the resultant or feeder voltage equal to *ED*. As the primary is rotated out of this position, say, about 40 degrees, or to *C*, the resultant of *EO* and *OC* is *EC*, which is equal to *EX*. Rotating the primary through an angle of nearly 90 degrees, or to *OB*, so that *EB* equals *EO*, the regulator is in the neutral position and neither boosts nor lowers. Completing the full range of 180 electrical degrees, the secondary voltage *OA* is directly additive to the bus-bar voltage *EO*, and the resultant or feeder potential is *EA*, the regulator now being in the position of maximum boost.

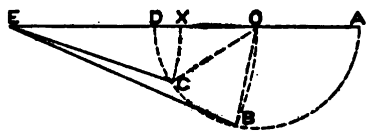


Fig. 159.

Comparing the single-phase and polyphase types of induction regulator above described, the important difference will have been noted that in the former the generated secondary voltage is in phase with the primary *E.M.F.*, and is variable because the amount of flux through the secondary changes with the angular position of the primary, while in the latter the flux acting through the secondary and the voltage generated in the secondary are constant, the value of the resultant voltage depending on an actual phase displacement between primary and secondary *E.M.F.'s*.

Regulators of the induction type are adapted either for hand operation or, especially in the larger sizes, for electrical operation by means of a small motor, the motion of the actuating shaft being communicated to the rotor through a worm wheel. When electrically operated they may be made to control automatically the voltage at a distant point by having the action of the driving motor made dependent on a relay controlled by pressure wires from the end of the feeder, or by equivalent means. The appearance of an electrically operated unit is shown in Fig. 160.

Fig 160.

Besides their use for the control of feeder voltage, polyphase regulators are frequently employed in conjunction with rotary converters as a means of varying the continuous-current voltage. When so used they are generally connected in the low-tension circuit between the transformers and the converter collector rings as described in Chapter VIII.

The induction regulator lends itself readily to the construction of very large units where the conditions demand a considerable range of voltage on heavily loaded feeders. Regulators as large as 800 kilowatts capacity have been successfully constructed, and even larger outputs are feasible. A regulator of the size mentioned would be able to raise or lower by 5 per cent (equivalent to a total range of 10 per cent) the voltage of a circuit carrying a load of 16,000 kilowatts, or to give a total voltage range of 20 per cent on a circuit of 8,000 kilowatts.

The approximate weight and dimensions of standard three-phase low-potential induction regulators in the smaller sizes ordinarily used is shown by the following table, which covers regulators boosting or lowering by 10 per cent:

Kilowatt Capacity of Regulator.	Diameter of Base.	Height.	Weight Lbs.
9.5	26″	48″	1400
19.0	26″	54″	1800
38.0	35″	66″	3400
76.0	35″	66″	4200

Power Factor and Efficiency of Regulators. — The power factor of the induction type may be as low as 85 per cent, while that of the switch type is considerably higher. Even this apparently low power factor has no appreciable effect on the power factor of the circuit controlled, owing to the fact that the kilowatt capacity of the regulator is so small a proportion of the energy delivered by the circuit in which it is connected.

The efficiency in sizes from 5 to 25 kilowatts in the polyphase type will range from 88 per cent to 92 per cent at full load. In larger sizes the efficiency reaches 95 per cent. Thus in small sizes the losses will amount to from 8 to 12 per cent of the capacity of the regulator, equivalent to about 0.4 to 0.6 per cent of the capacity of the circuit controlled, assuming the amount of boost or reduction to be 5 per cent.

Methods of Cooling. — Since the losses in a polyphase induction regulator are about twice as great as in a transformer of the same kilowatt output, it follows that artificial cooling must be resorted to in relatively small sizes. Regu-

lators of the oil type can be self-cooled up to about 40 kilowatts capacity. In larger sizes they are equipped with a water-cooling coil, as similarly used in large transformers, or they may be constructed in the air-blast type.

Line-Drop Compensator. — Whatever method is adopted for compensating for the voltage drop in feeders, whether by altering the bus-bar voltage or by the use of individual feeder regulators, it is necessary in order to secure good regulation that some means be employed that will at all times indicate in the station the voltage that is being delivered at the receiving end of the feeder. While this can be accomplished by pressure wires run from the end of the feeder back to the station, where they are connected to a voltmeter, this method is cumbersome and expensive, especially in the case of numerous and long feeders. The equivalent result is secured by a device invented by Mr. R. D. Mershon, which may be termed a line-drop compensator, the principles of which are explained below.

Suppose that at the station there were artificially produced three *E.M.F.'s* proportional to, and in phase with, respectively, the *E.M.F.* impressed upon the line at the station, the *E.M.F.* consumed by the reactance of the line, and the *E.M.F.* consumed by the resistance. If it be also supposed that these three separate *E.M.F.'s* are combined in the same way as are their counterparts in the line, it follows that their resultant will be equal to and in phase with the *E.M.F.* at the far end of the line, and that a voltmeter actuated by this resultant *E.M.F.* will read the delivered voltage. The device in question effects this result by providing in the station a miniature counterpart of the line, having the same relative reactance and resistance, and

through this artificial circuit the voltmeter is connected as shown below.

In the diagram, Fig. 161, the potential transformer *C* gives at its secondary terminals an *E.M.F.* proportional to that of the generator *G*. The inductive resistance, *a*, and the ohmic resistance, *b*, are adjusted with respect to the current from the series transformer, *d*, so that with a

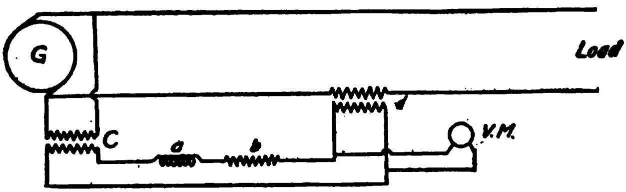


Fig. 161.

given current flowing through them, the reactive and ohmic drop across *a* and *b* respectively, have the same value relative to the *E.M.F.* of transformer *C* as the reactance and resistance *E.M.F.*'s of the line have to the generator *E.M.F.* Hence, the voltmeter *VM* reads, the voltage of *C* reduced by the drop across *a* and *b*, — in other words, it gives the same reading as it would if it were at the receiving end of the circuit.

CHAPTER XI.

LIGHTNING PROTECTION AND LINE CONSTRUCTION.

Lightning Protection. — There is no problem with which the electrical engineer has to deal that presents greater difficulties in the way of a positive solution than that of lightning protection. The uncertainty among the highest authorities as to the exact nature of lightning phenomena is partly accountable for this state of affairs. The oscillatory character of the direct lightning stroke has been established beyond a doubt, but experience with lightning effects would indicate that the frequency of the oscillation is of widely varying characteristics. For this reason, no one single device can be infallibly depended on to protect electrical apparatus from all kinds of lightning phenomena. In other words, there is not, and cannot be, a universal lightning arrester.

Under the term lightning protection is understood to be included protection against high-potential phenomena of all sorts, whether produced by lightning or other atmospheric disturbances, or due to conditions arising in the circuit itself.

Excess voltages traceable to lightning or to other causes extraneous to the circuit may be divided into three principal classes, as follows:

First. The true lightning discharge, as when the transmission lines are in the direct path of the stroke.

Second. The cumulative discharge due to a gradual and sometimes enormous rise of potential from a changing electrostatic condition of the atmosphere. This class of phenomenon is probably of the same nature as the excess potentials that may exist where, on a long transmission, one portion of the line is subjected to different atmospheric conditions from those prevailing in another part. This condition seems to be frequent where there is considerable difference of elevation in different portions of the circuit, as where the line crosses a mountain range.

Third. The secondary discharge due to secondary currents induced in the line by a parallel lightning stroke. In this case the line plays the part of a transformer secondary, regarding the path of the lightning stroke as the primary.

Among the abnormal potentials arising from conditions within the circuit are those due to switching, grounds, and short circuits. These are of the kind referred to on page 251, in the discussion of the oil switch, and are frequently spoken of as *surges*.

The high-voltage disturbance resulting from any of the above-mentioned phenomena is alternating in character. The frequency of the alternations, particularly the frequency of lightning discharges, has long been a subject of discussion among engineers, and while it is generally agreed that the surge effects due to switching, short circuits, and grounds are usually of moderate frequency, say about one thousand cycles or so, close observation has indicated that in some cases the voltage disturbance is one having an enormously high frequency. To be effective under all conditions, therefore, lightning arresters should be able to relieve the system of high-potential stresses at any frequency

encountered in service. They should also be able to interrupt promptly and with certainty the flow of current from the line which tends to follow every static discharge. To fulfill both these requirements in an eminent degree has proved a difficult problem, which is still engaging the most careful study and experiment.

Commercial Types of Lightning Arrester. — Although much is yet to be learned about the most suitable form of lightning protection for alternating-current circuits, experience has narrowed down the many ancient devices to one or two principal types. The simplest of these is the so-called "goat-horn" arrester shown in outline in Fig. 162. This consists simply of two wires bent away from each other like a pair of goat horns, and separated at the bottom by a space appropriate to the voltage at which the arrester is intended to discharge. Connections are made at the base of each horn to line and to ground respectively. The current from the line which follows the discharge establishes an arc, which travels upward along the horns under the influence of the heated vapor and of magnetic repulsion, growing longer and longer, due to the spread of the horns, till it is finally extinguished. A series resistance is usually inserted to limit the current flow, which would otherwise

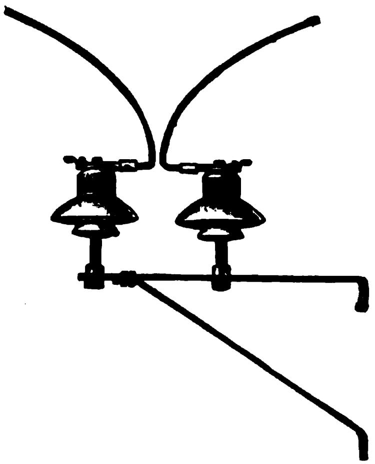


Fig. 162.

rise to an excessive value, being, in fact, that due to short circuit.

This type of arrester is cheaply installed, and may be set up out of doors where danger from fire due to the arc is avoided. When used without series resistance it has the advantage of having a practically constant break-down point on all frequencies; but since a series resistance must usually be employed, this feature loses something in importance. A series resistance, moreover, when used with any type of lightning arrester, is now considered detrimental inasmuch as by skin effect it interposes considerable reactance to discharges of high frequency, and correspondingly limits the range of the arrester.

The other chief type of arrester, and the one which is mainly used in this country, consists of a number of metal balls or cylinders separated by short air gaps. A number of these cylinders are mounted on a porcelain base, forming a so-called unit, and sufficient units are connected in series so that the total gap space, i.e., the aggregate sum of the individual gaps, shall be appropriate to the voltage at which the arrester is intended to discharge. A unit of this type is illustrated in Fig. 163. There are 33 cylinders, each 1 inch high and $\frac{7}{8}$ inch diameter, the gap space between cylinders being $\frac{1}{32}$ inch. No series resistance is used with this type of arrester, but it is customary to connect a shunt resistance around about half the total number of gaps. This shunt resistance is found to assist materially the interruption of the resulting current-flow without affecting detrimentally the ability of the device to discharge high-frequency voltages. The arc-extinguishing action of these arresters is dependent mainly upon the cooling effect of the many metal cylinders, the large aggregate surface of

which prevents the formation of any heated conducting vapor, and so insures that the arc shall be promptly extinguished at the zero point of the wave after the lapse of only two or three cycles at most. In this respect the action of this type is considered superior to that of the horn arrester, where it frequently happens that the arc is not extinguished till after several seconds. Considerable importance is also attached to the metal of which the cylinders are made, which is commonly a compound of bronze, of which the vapor is understood to have certain non-conducting properties.

Fig. 163.

The general appearance of the cylinder type of arrester when assembled complete, is shown in Fig. 164, which gives the connections used on a three-phase circuit, and which also shows the shunt resistance and the method of connecting it. The arrester illustrated is suited for use on a circuit having a working potential of 12,000 volts between lines. At the top of the figure is seen a set of switches by which the arrester may be disconnected from the line for inspection.

As already indicated, the number of units which should be included in an arrester connected to any system is affected by the length, elevation, and insulation of the line,

as well as by the load conditions and other factors, so that it becomes necessary to adjust an arrester to the particular circuit to which it is connected. This is conveniently effected by means of adjustable needle gaps (seen just beneath the disconnecting switches in the figure) which

Fig. 164.

can be set for any desired potential, after which more or fewer of the cylinder gaps are short circuited by small metal strips till the discharge will by preference pass through the arrester rather than across the needle points.

Installing Lightning Arresters. — The principle on which a lightning arrester is selected for any particular voltage,

is that it must be the weakest point in the line, — in other words, the adjustment must be such that any excess potentials will be discharged through the arrester rather than find a path to ground through transformers or other electrical apparatus which the arrester is intended to protect. It is customary to install arresters at each end of each line, in the generating station and in the substation respectively. In the case of long transmissions it is also considered advisable to install one or more sets of arresters along the line, at distances of, say, ten to twenty miles, or at points where excess potentials are frequent. In the case of local distribution circuits at one or two thousand volts, arresters are installed on the poles at intervals of about a thousand feet, and are also advisably used wherever there is a group of transformers.

In the installation of arresters, whether in the station or on the line, the ground connection must be made with the utmost thoroughness and care, for on the continuity and effectiveness of the ground connection the operation of the arrester absolutely depends. The ground is preferably made with a copper sheet about $\frac{1}{16}$ inch thick and having at least four square feet of surface, buried in powdered coke in soil which is always damp. The ground wire, which is best made of flexible copper strip having a cross section not less than that of $\frac{3}{8}$ inch round wire, should be carefully soldered and riveted to this plate, the connection from the arrester to ground being made as short and as direct as possible. Where there are metal flumes, pipes, or rails, it is advisable to rivet and solder the ground wires to them in addition to the connections to the copper plates.

Choke Coils. — Owing to the oscillatory character of

the high-potential discharge, it would seem as if a choking coil placed between the arrester and the apparatus to be protected would offer such resistance to the discharge as always to force it through the arrester and thence to ground. In actual service it has been found that the choke coil does not always seem to have this effect, at least to a marked degree, and for this reason its usefulness has been questioned. It is, nevertheless, an inexpensive adjunct, and since it seems to present no features of disadvantage, and may be of assistance under certain conditions, engineers are at present inclined to favor its use. A typical choke coil for use on a high-tension line is illustrated in Fig. 165.

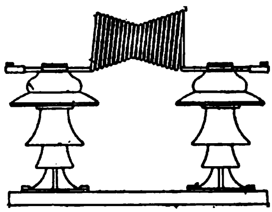


Fig. 165.

Insulators. — A desirable insulator for line use should have the following qualifications, which are set down in the approximate order of their importance.

1. A large dry creepage surface.
2. High resistance to electrical puncture.
3. High mechanical strength.
4. Ability to withstand the action of the elements without roughening or cracking.
5. Freedom from charring, softening, or other change of physical properties under continued electrical, mechanical, or thermal stress.
6. Ease of handling and transportation.
7. Reasonably non-fragile properties.
8. Comparative cheapness.

Porcelain satisfies more of these conditions than does any other commercial product, and hence is the material

most commonly employed. When used for insulators it should be thoroughly vitrified and homogeneous. The material should be non-absorbent of moisture, and not dependent for its insulating properties on the surface glazing, the function of which is merely to give a smooth exterior so that dust or moisture may not be retained on the surface. While the general character of a porcelain insulator may be roughly gauged by breaking it and examining the appearance of the fracture, and by determining the absorptive properties of the broken surface, it is essential, in order to verify the actual insulating strength, to subject each insulator to a high-potential test.

This test is conveniently made by placing a number of inverted insulators in a metal pan which is filled with brine deep enough to immerse the insulators up to the point where the tie wire is to be attached. The brine solution is also poured into the pin holes of the insulators up to the depth of the threading. A series of metal rods, connected electrically together and to one side of the testing circuit, dip into the brine in the pin holes, and the other side of the circuit is connected to the pan in which the insulators are contained. Application of the test pressure is now made for the desired time, usually four to five minutes, at double the working voltage on which the insulator is to be used. Any insulators that are not perfect will usually fail during the first minute of the test, the puncture being manifested by a shower of bright sparks.

In addition to the mode of testing previously described, a so-called "dry" test is sometimes made by mounting the insulator in its normal upright position on a metal pin, a short length of line wire being attached to the top groove in the regular way. The test pressure is then applied

between the pin and the wire. An important modification of the preceding is to subject the insulator during this test to a brisk spray of water, simulating a heavy rain storm. This is known as the wet test, and the standard conditions usually call for a water precipitation equivalent to a one-fifth inch per minute rain fall, the direction of the spray being at 45 degrees from the vertical. This test gives an indication of the ability of the insulator to maintain the under surfaces in a dry condition.

Fig. 166.

A good margin of safety is usually found in any insulator that will withstand for fifteen minutes a dry test of three times the normal working voltage. The criterion under the wet test is rather indefinite, owing to the uncertain effect of air currents, splashing, and other factors, but may be placed at about one and one-half times normal voltage for a fifteen-minute period.

Fig. 166 shows one form of high-tension porcelain insulator mounted on its iron pin. This insulator, made by the Ginori Company of Italy, is tested at 60,000 volts, and is used on a 30,000-volt transmission in India. It is $8\frac{1}{4}$ inches in height, $6\frac{3}{4}$ inches in diameter at the widest part, and weighs 7 pounds, the entire insulator being molded in one piece.

The type developed by American engineers and used on

most of the notable high-tension transmission systems, conforms to the general design shown in Fig. 167, which illustrates the principal features of an insulator manufactured by the Locke Company. It is built up, as seen, of four separate shells cemented together, and is suited for use on circuits of 60,000 volts. The test pressure is 120,000 volts for five minutes on the completed insulator, the separate shells being individually tested at an average of 50,000 volts each for two minutes. The principal dimensions appear in the cut, and the net weight is about 25 pounds.

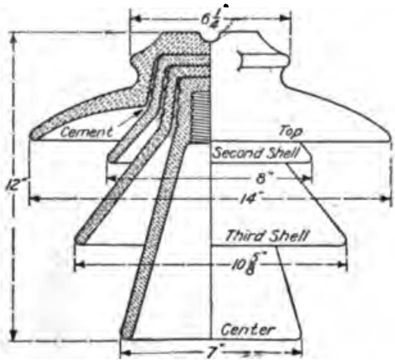


Fig. 167.

This general type of insulator, using from two to four or even five separate shells, according to the conditions, is considered by American engineers and manufacturers to be preferable to the one-piece type for work at about 15,000 volts and over. The individual shells being relatively small and light, it appears easier to secure a homogeneous and reliable structure in this way than if it were attempted to mold in one piece a single block of porcelain of the intricate shape and ample dimensions necessitated at the higher voltages.

While porcelain has been used for insulators to the practical exclusion of all other materials, the use of glass, which has many of the desirable characteristics of the former material, has had a considerable application, especially for circuits under 10,000 volts. In some cases, glass insula-

tors have been successfully used on very high voltages, notably in the installation at Provo, Utah, which transmits at 40,000 volts. Nevertheless, when in massive shapes, glass appears somewhat difficult to anneal, and hence is not as strong mechanically as desirable, nor as well able to resist extremes of temperature. These disadvantages have appeared to militate against any extensive use of glass, which has had only a limited application up to the present.

Line Construction. — The great majority of transmission lines are carried on wooden poles with one or two circuits per pole, reference being had to three-phase transmissions only, since other systems, which require a greater weight of copper, are used only in exceptional cases, or for local distribution circuits. Where the pole line carries a single circuit, the wires are preferably arranged in an equilateral triangle, to equalize the inductance of each phase, one wire being carried at the top of the pole so that but one cross-arm is required. In the case of two circuits per pole, four of the wires may be carried on one cross-arm at the top, and the remaining two on a second cross-arm beneath. With this arrangement the wires of each circuit are spaced in a triangle as before, except for having the apex downward, — an arrangement which facilitates the lineman's access to the wires from below. The poles are of such a length that the lowest line wires shall be at least 20 feet above the ground at the middle of the span. The distance between poles depends largely on the number and size of conductors carried, and on the size of pole. Good practice establishes about the following averages:

Pole Spacing.

No. of Conductors.	Size of Conductors, B. & S.	Top Dia. of Pole.	Spacing of Pole.	No. of Poles per Mile.
3	Nos. 6–1	7 in.	150 ft.	35
6	Nos. 6–1	7 in.	150 ft.	35
3	Nos. 0–4/0	8 in.	125 ft.	42
6	Nos. 0–4/0	8 in.	110 ft.	48
3	250,000–400,000 cm.	9 in.	100 ft.	53
6	250,000–400,000 cm.	10 in.	80 ft.	66

The above values are for straightaway work, and closer spacing is necessary on curves.

The distance between line wires depends mainly on the voltage. The table below gives desirable spacings:

Line Voltage.	Conductor Spacing.
2,000– 6,000 incl.	2 ft. 4 in.
10,000–20,000 incl.	3 ft. 4 in.
20,000–30,000 incl.	4 ft. 0 in.
30,000–40,000 incl.	5 ft. 0 in.
40,000–50,000 incl.	5 ft. 0 in.
50,000–60,000 incl.	6 ft. 0 in.

During the last few years steel towers have been extensively used for supporting the conductors on the longer transmission systems, especially those at 40,000 volts and over. This construction is deemed to afford several important advantages, chief among which are strength and permanence due to the absence of the decay which ultimately weakens and destroys wooden poles. Other advantages are that metal towers are not subject to injury from lightning, or to burning, and that by reason of the much longer spans that may be used, the number of insulators, and thus the number of points where trouble may occur, is reduced to a minimum. The general design shown in

Fig. 168 is illustrative of the structures referred to, and shows a tower built up of light but strong angles and channels, securely cross-braced. This tower carries two three-phase circuits spaced 6 feet between conductors. It is 17 feet square at the base, 60 feet high over all, and measures 50 feet to the lowest conductor. The net weight is 4,000 pounds.

The towers are shipped knocked down and are assembled in the field. Towers of this general design are used on the 160-mile transmission of the Mexican Light and Power Company, to Mexico City and to El Oro, and on most of the other important long-distance lines installed during the last few years.

In order to secure the maximum immunity from interruptions, a duplicate pole line is sometimes installed with one or two circuits per pole, as the case may be. In this event, whether the transmission line is erected on wooden poles or on steel towers, the pole lines are separated by a space depending on the height of the pole, so that damage to one line may not be communicated to the other. In transmissions of this character, whether using a single or a double pole line, a wide space is cleared on either side so as to protect the lines from injury by falling trees. For this purpose power companies usually acquire control of a strip of land of the necessary amount, the right of way for the duplicate steel tower lines from Niagara Falls to Toronto being, for example, 80 feet.

In the case of wood pole lines with maximum spans of about 150 feet, soft-drawn, solid wire is generally used for the line conductors where the copper cross section is not too great to prevent ease of handling. In the case of steel tower lines, where spans of 400 to 600 feet are commonly

employed, stranded conductors of hard-drawn copper are preferably used, as these have about 50 per cent greater

Fig. 168.

tensile strength for the same cross section, besides the advantage of flexibility and greater ease in handling. It is con-

sidered advisable to string an additional conductor, usually of galvanized iron, above the transmission line. This additional conductor is grounded at both ends of the line and at frequent intervals along the line, and appears to be of much assistance in obviating troubles from lightning. In Fig. 168, a ground wire of this sort is carried on a standard which is seen at the top of the pole between the two line circuits.

Where parallel transmission lines are run on the same or on adjacent poles, it is customary to transpose the conductors at intervals, in order to minimize the effect of mutual induction between the separate circuits and to reduce the inductive effect of the power wires on telephone, telegraph, or other power circuits in the vicinity. Transposition is effected by changing the relative position of the several line wires so that the wire carrying phase No. 1, for instance, will be first at the top, then at the lower right-hand corner, and at a further point at the lower left-hand corner of the triangle. One or more complete spirals are made in this way throughout the length of the transmission, according to the conditions.

Telephone lines for intercommunication between stations are ordinarily carried on the same poles that support the transmission wires, and must be transposed at frequent intervals, or the strong induction from the power circuits will entirely prevent conversation. Owing to the high potentials which are sometimes accidentally communicated to the telephone wires by induction or by contact, the practice has recently been inaugurated of connecting the telephone instruments to the line through a small highly insulated transformer having a 1 : 1 ratio, so that no dangerous potentials may get through to the telephone terminals.

CHAPTER XII.

TWO-PHASE SYSTEM.

Polyphase Systems and Combinations. — Any arrangement of conductors, carrying two or more single-phase alternating currents, having a definite phase relation to each other, constitutes a polyphase system. The systems commonly employed for the generation and distribution of power by polyphase currents are the two-phase and the three-phase systems.

Polyphase currents are usually produced by alternators the armatures of which are so wound that the electromotive forces at the terminals correspond to the number of phases, and arrive at a maximum in a fixed and definite relation to one another.

In the two-phase system the two electromotive forces and currents are 90 degrees, or one-fourth of a cycle, apart. The relations of the curves to each other, and their instantaneous values, can be seen from the development of the diagram of single harmonic motion (Fig. 169). The maximum of one wave occurs when the value of the other is zero. If the pressure in any one of the coils *Oa* or *Ob* is 1, the pressure between the ends *ab* is $\sqrt{2} = 1.414$.

The windings of a polyphase machine may be combined in a number of ways, each affecting the relation of the electromotive forces of the outside conductors, as shown in Figs. 170 to 173. These diagrammatically represent

the coils of a two-phase machine, in which the electromotive forces may be considered as being either generated or absorbed. In Fig. 170 all the coils are in series, form-

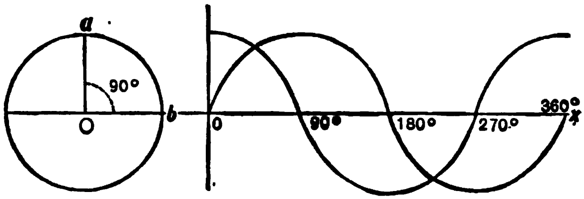


Fig. 169.

ing a continuous winding, tapped at four points. Leads 1 and 2 constitute the circuit of one phase, and 3 and 4 that of the second phase. The *E.M.F.* between the wires of different phases is 1.414 ÷ 2 times that between leads of the same phase. In Fig. 171 the windings of each phase are separate. This arrangement can be made interlinked by joining the two circuits where they cross, thus forming a common center, as shown in Fig. 172. The relation of *E.M.F.* is the same as in Fig. 171. The grouping of coils, shown in Fig. 171, may also be made interlinked by joining leads 4 and 2 (Fig. 173), which become a common return for 1 and 3. The *E.M.F.* between the two outgoing wires is 1.414 times that between each outgoing wire and the common return.

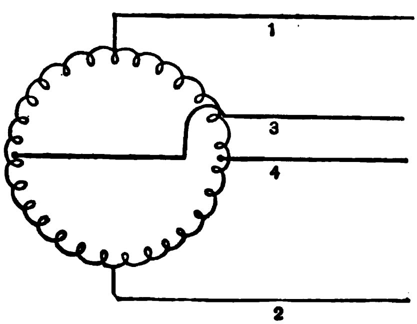


Fig. 170.

The windings of interlinked systems are classed according to their connections as "Ring," or "Star." Figs. 170 and 172, respectively, show the ring and star connections of the two-phase system.

In the three-phase system, the star and ring connections, respectively, are usually designated as Y and Δ (Delta), from their resemblance to these symbols. The winding

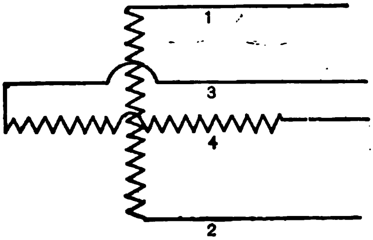


Fig. 171.

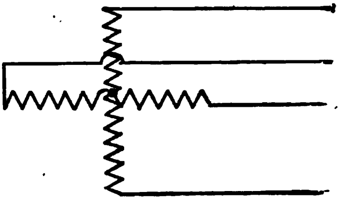


Fig. 172.

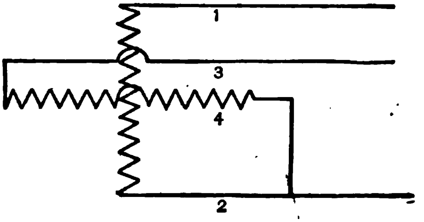


Fig. 173.

connections of most commercial two-phase machines are interlinked.

No matter what the arrangement of the winding may be in a polyphase machine, whether the coils are interlinked, or separately grouped, ring or star connected, the principles of action are the same, and the characteristic polyphase results are equally present.

Polyphase systems have two desirable features: First,

the supply of power is continuous and uniform, thus increasing the capacity of apparatus, and in some systems, that of transmission conductors; and, second, the use of revolving types of induction apparatus is permitted, which do not require any form of moving contacts.

Transformer Connections. — A number of combinations of two-phase circuits can be made by suitably arranging

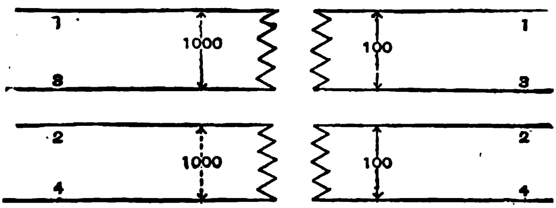


Fig. 174

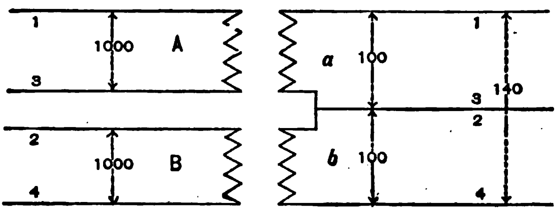


Fig. 175.

transformers with due regard to the generator windings. Fig. 174 shows the connections commonly used for lighting and transmission of power. The arrangement consists of two single-phase transformers, the phases being separated in both primary and secondary. Two of the secondary leads are sometimes joined (Fig. 175), making a common return for the other wires. The two circuits being 90 degrees apart, the voltage between 1 and 4 is $\sqrt{2}$ times that between the outside wires and the common return, and

the current in the common return is $\sqrt{2}$ times that in each of the outers. This arrangement is best adapted for supplying current of minimum potential to apparatus in the vicinity of the transformers. It is more frequently used in connection with motors operating from the secondaries of the transformers. Fig. 176 shows another arrangement of transformers where the common return is used on both primary and secondary. As will be explained farther on, this connection is permissible only when the power of the

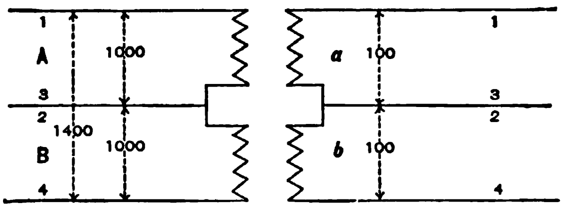


Fig. 176.

two circuits is consumed by one unit, or when both sides of the system are balanced.

Two-Phase to Three-Phase. — It is possible, by a combination of two transformers, to change one polyphase system into any other polyphase system. The transformation from two-phase to three-phase, or vice versa, is effected by proportioning the windings as shown in Fig. 177, commonly called the Scott connection. One transformer is wound with a ratio of transformation of 1,000 to 100; the other with a ratio of 1,000 to 86.7. The secondary of this transformer is connected to the middle of the secondary winding of the first. In Fig. 178, *AB* represents the secondary volts from *A* to *B* in one transformer, called the main transformer. At right angles to *AB* the line *CO* represents,

in direction and quantity, the pressure O to C of the second transformer, called the teaser. From the properties of the triangle it follows that, at the terminals A, B, C, three equal pressures will exist, each differing from the others by 120 degrees, and giving rise to a three-phase current.

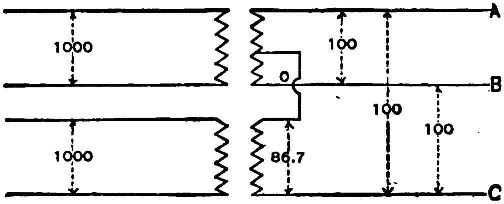


Fig. 177.

For this transformation on a small scale, a sufficiently close approximation is secured by the use of standard transformers, the teaser having a ratio of 10 to 1, and the main transformer a ratio of 9 to 1.

The current in the winding AB, being a resultant of the other two phases, is greater than if the change to three-phase were not made; and, consequently, for the same heating, necessitates a larger cross section of copper in the secondary. This current being 15 per cent greater than in a normal single-phase transformer, the secondary copper must be larger in the ratio of $\overline{1.15}^2$ to $\overline{1.00}^2$, or an increase of 32 per cent. This means that the main transformer, considering he total material in its construction, is the equivalent of a transformer of about 8 per cent greater output. Taking both transformers together it is seen that the two-phase, three-phase transformation involves the equivalent of 4 per cent additional capacity. If the two transformers are made interchangeable the teaser

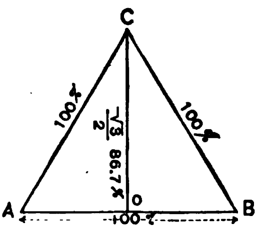


Fig. 178.

must be as large as the main transformer, and the total increase amounts to 8 per cent. The secondary of each interchangeable transformer has two taps, giving 50 per cent and 86.7 per cent of the full voltage, so that either transformer can serve as the teaser by using the proper terminals.

In the long-distance transmission of power the generators are sometimes wound two-phase, and the secondary distribution at the receiving end is likewise by the two-phase system, while on account of the saving in copper

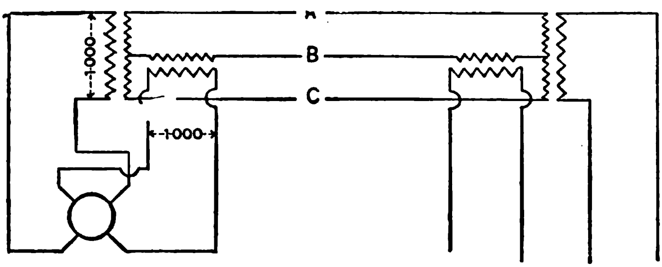


Fig. 179.

the transmission is by the three-phase system. Such is the arrangement of the apparatus at the generating end of the Niagara-Buffalo plant. The distribution in Buffalo, however, is mainly by the three-phase system. Fig. 179 shows the transformer connections for changing two-phase to three-phase and back again.

Two-Phase Four-Wire System. — This system consists of two separate circuits, derived from two armature windings in quadrature with each other, which may be either independent or interlinked, or from a continuous armature winding tapped at four equidistant points. The practical application of this system is illustrated in Fig. 180. Each

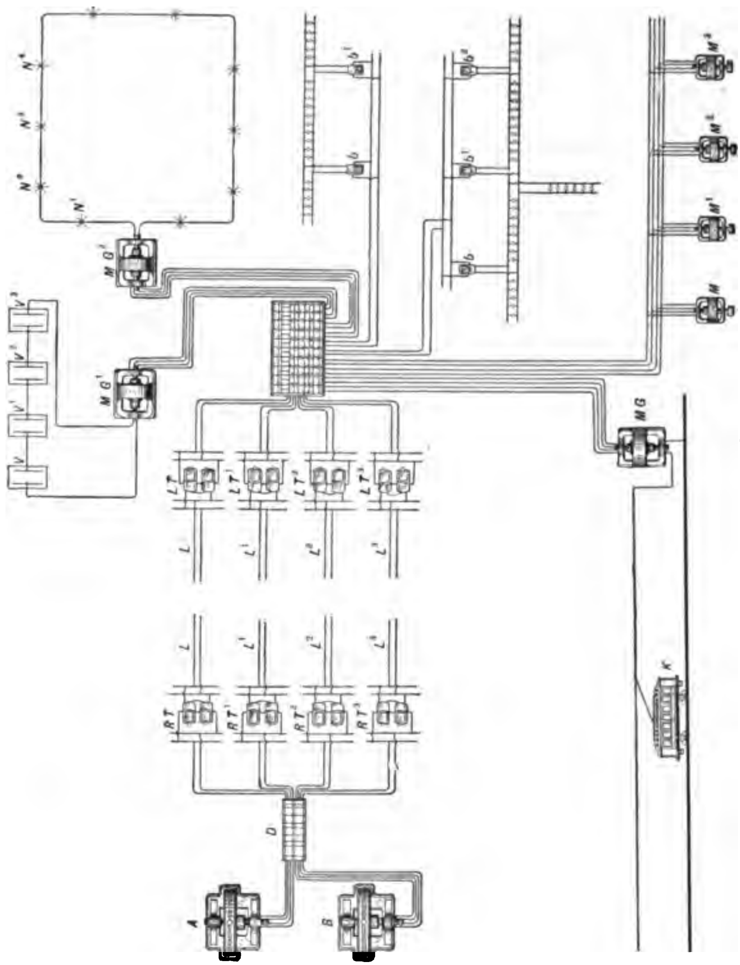


Fig. 180.

of the two generators *A* and *B* delivers two-phase currents of low potential to the step-up transformers RT, RT^1, RT^2, RT^3, through the switchboard *D*. The transmission lines L, L^1, L^2, L^3, receive and transmit current, at a high pressure, to a substation conveniently located with reference to the districts where lights and motors are to be supplied. The high-potential current is here reduced by the transformers LT, LT^1, LT^2, LT^3, to a commercial pressure suitable for local distribution, through the switchboard *F*. Beginning at the bottom of the figure, the first four-wire system is used to supply alternating current to the rotary converter *MG*, which, in turn, delivers direct current at 500 volts to a trolley line operating the street-car systems *K*. The second circuit supplies the motors M, M^1, M^2, M^3, either of the synchronous or induction type. The next four-wire system is divided into two distinct circuits, supplying current to incandescent lamps through the transformers b, b^1, b^2. The next circuit supplies current for arc lighting through a motor generator MG^2. A rotary converter is also operated from the last circuit, and delivers low-voltage current for electrolytic purposes. The rotary converters in practice are supplied with transformers, not shown in the diagram, which deliver, at the rotary terminals, an alternating current of the proper voltage.

The two single circuits must be balanced as nearly as possible, and for this purpose the four wires must be carried through the same district to be supplied with power or light. In order to obtain economy in copper in a secondary system of distribution, three-wire mains may be used. In the two-phase four-wire system, where motors are to be supplied, the two independent three-wire circuits must be brought together, making six wires in all.

The measurement of power by this system is obtained by the use of a wattmeter inserted in each circuit, as in a single-phase system. The sum of the two readings gives the total power supplied. In a balanced system, twice the reading of one wattmeter will give the power.

Two-Phase Three-Wire System. — By joining any two

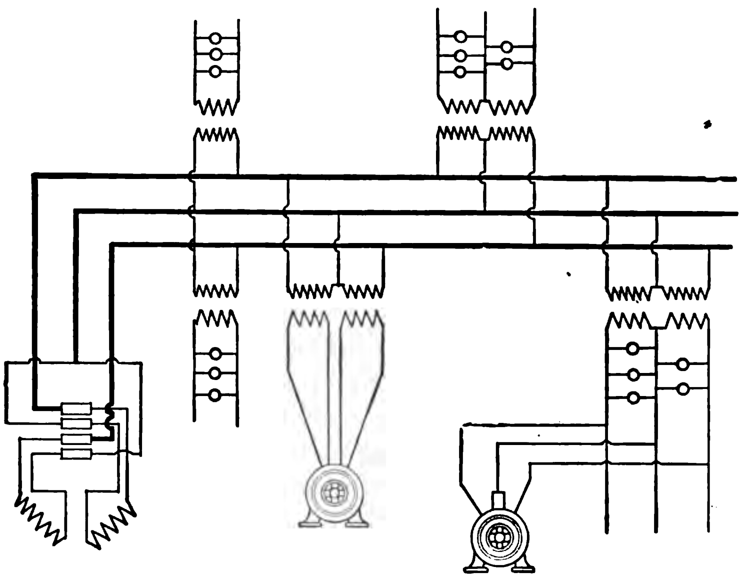


Fig. 181.

conductors in the four-wire system, a common return is made for the two circuits. This arrangement of circuits is called the two-phase three-wire system. As previously shown, the pressure between the common conductor and the others is 41.4 per cent higher than that which existed before. Since the current in the common conductor exceeds by this same percentage the current in the outers,

the common conductor must be of suitably larger cross section, in order to keep the loss the same.

The general application of this system is shown in Fig. 181. Two terminals of the generator coils are united; and the three leads, forming an interconnected two-phase system, are run to wherever motors and lights are to be supplied. When motors are used, connection is made directly with the main leads, or, if the motors are wound for low voltage, connection is made through two transformers. The motors, which are of the ordinary two-phase type, may have their terminals connected either on the three-wire or four-wire system.

Where lights are supplied, the transformers may be connected singly to only one circuit, or in pairs on two circuits, with a common return. In practice, it is essential that both phases be equally loaded.

In this arrangement of conductors there is an unbalancing of both sides of the system on an inductive load, which exists even though the energy load is equally divided. This unbalancing is due to the fact that the *E.M.F.* of self-induction in one side of the system is in phase with the effective *E.M.F.* in the other side, thus distorting the uniform current-distribution in both circuits.

The distribution of currents and electromotive forces in the three conductors in the single-phase three-wire, the three-phase and the two-phase three-wire system, is shown in the following table. The figures are the results of experiments to determine the self-induction of underground tubes.

The voltage per circuit is always equal for equal loads in the single-phase three-wire and in the three-phase systems, but the induction unbalancing of the two-phase three-

175 Feet 250,000 C.M. Edison 3 Conductors. Main Tube.	Amperes in Conductors.			Volts Between Conductors.									Watts Lost in Line Governing Capacity of Tube.
				At Feeding Point.			At End of Line.						
							60 Cycles			125 Cycles.			
	a	b	c	a & b	b & c	a & c	a & b	b & c	a & c	a & b	b & c	a & c	
Single-Phase 3 Wire	400	0	400	100	100	200	97	97	194	96.6	96.6	193.2	2,400
Three-Phase 3 Wire	462	462	462	100	100	100	94	94	84	93.4	93.4	93.4	4,800
Two-Phase 3 Wire	400	566	400	100	100	142	90	97	134	87.	99.	136.	4,800

wire system is beyond the range of practical operation. These results were obtained with low-tension systems and moderate drops. The unbalancing effect is much greater with higher voltage and drops. The four-wire two-phase system would, of course, show no such unbalancing.

CHAPTER XIII.

THREE-PHASE SYSTEM.

Curves of E.M.F. — The *E.M.F.* impulses in a three-phase system follow one another at intervals of 120 degrees. The instantaneous values and the relation of the phases, developed from the diagram of simple harmonic motion, are shown in Fig. 182. The curves *a, b, c*, represent the electromotive forces produced by three sets of generator coils. If in the circle the distance from *O* to *a*, *b*, and *c*, be taken

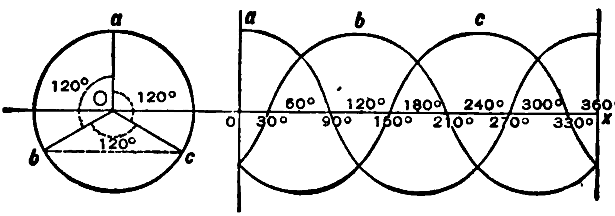


Fig. 182.

equal to 1, it follows from the diagram that the lines joining *a*, *b*, and *c* are equal to $\sqrt{3} = 1.732$. That is, the pressure between the ends of any two of the generator coils in a three-phase system is 1.732 times that between the common juncture *O* and the terminals of the coils.

It will be seen from the diagram that each one of the coils successively serves as a return for the other two, and that the algebraic sum of the currents in the system is

zero. The three-phase system may be resolved into three single circuits, with a common or grounded return. The sum of the currents being zero, no current will flow in the return conductor, and it may be dispensed with. The system then becomes the ordinary *Y*-connected arrangement.

Transformer Combinations. — The ring and the star connections of three-phase windings — whether of armature in

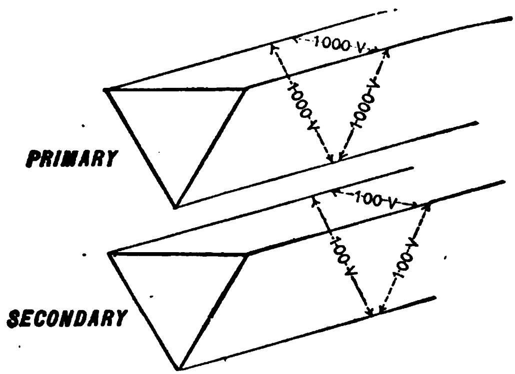


Fig. 183.

which the electromotive forces are induced, or transformer or motor in which the electromotive forces are absorbed — are designated by the symbols Δ (delta) and *Y* respectively. Figs. 183 to 187 illustrate the various three-phase combinations of single-phase transformers in practical operation. Fig. 183 shows Δ connection of both primary and secondary terminals of transformers, having a ratio of 10 to 1. Fig. 184 shows three transformers, *Y*-connected in both windings. The ratio of pressures between any two corresponding terminals in primary and secondary is

the same as in the Δ arrangement. The individual transformers thus connected have fewer turns for the same voltage than when Δ connected, which is an advantage where the line voltage is high. The drawback to this

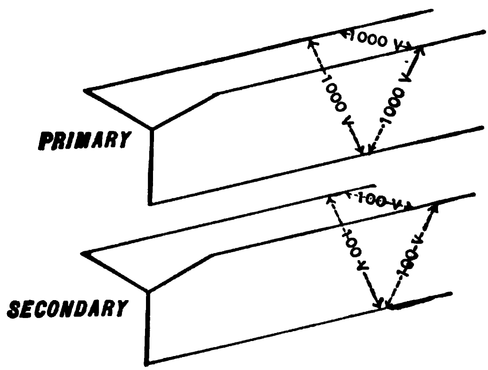


Fig. 184.

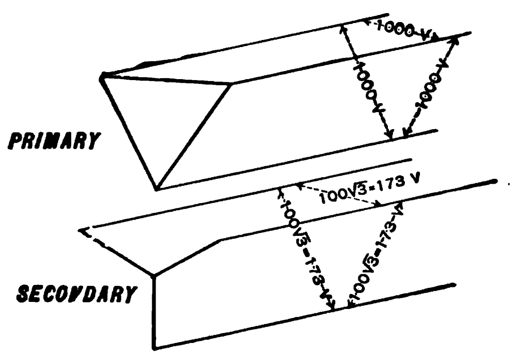


Fig. 185.

connection is the unbalancing of voltage and inequality of heating that are liable to take place unless all the neutrals are connected to each other and to the neutral of the generator. Fig. 185 shows a combination of Δ and *Y* con-

nection, the primaries of the transformers being connected Δ, while the secondaries are connected Y. A fourth wire may be led from the common center of the three secondaries. The pressure between this neutral and any one of the outside wires is $\frac{1}{\sqrt{3}}$ of the pressure between the outside wires. This arrangement is known as the "three-phase four-wire system," and is frequently used in secondary distributing systems, especially abroad. In Fig. 186, the primaries are connected Y, the secondaries delta.

A connection is sometimes made up of two transformers (Fig. 187) instead of three, this arrangement being usually called the "open delta" connection. The pressures between all three terminals are equal, that from the open side of the triangle on the secondary being due to the *E.M.F.* of the corresponding phase of the primary acting through the two transformers in series. This arrangement is frequently used with motors, its chief advantages being its simplicity, and permitting the use of available transformers when the motor cannot be fitted with three transformers of exactly the capacity wanted. Its disadvantage is that the continuity of polyphase working is destroyed in case of damage to one of the two transformers. Another disadvantage of the open delta arrangement is that 15 per cent more transformer capacity is required for the same energy than with the ordinary delta connection using three transformers. This disadvantage may not be so important in small transformers, which, when chosen in standard sizes, may be amply large for the work, but must be taken into account in any cases where the capacity is accurately figured.

In general, the combination of three transformers with

both sides connected delta is most convenient and desirable, for the reason that an accident to one does not prevent a continuance of the service. In this contingency it is

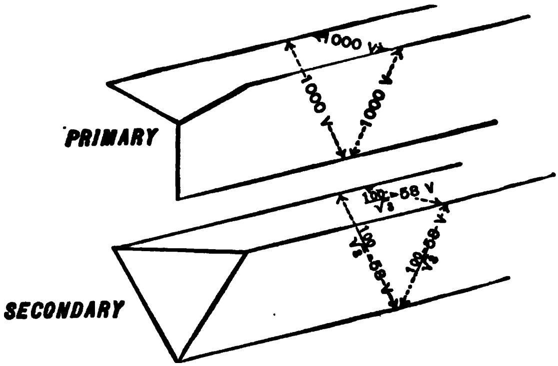


Fig. 186.

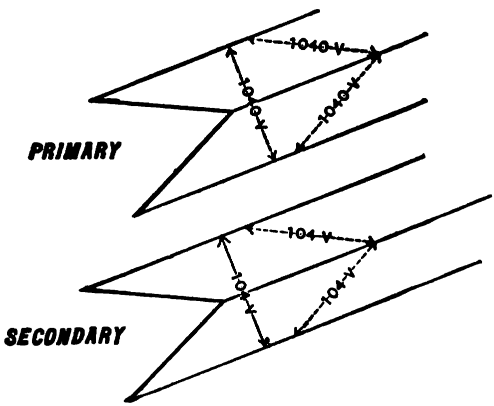


Fig. 187.

necessary that the load be reduced by about one-third (by 42 per cent, strictly speaking) to prevent overloading the remaining two transformers, which are thus reduced to the open delta connection.

Six-Phase Connections of Transformers. — This connection is much used with rotary converters and is illustrated by the diagrams on page 193 (Figs. 115–118 inclusive). It may be derived from any system of transformers connected in three-phase and having two separate secondary windings, by reversing one of the two sets of secondaries. The simplest method is the so-called diametrical connection which is described under the preceding reference.

Motor Connections. — Motors are connected to the

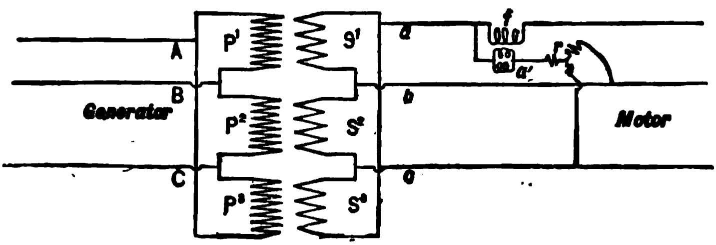


Fig. 188.

secondaries of three transformers in a three-phase system, as shown in Fig. 188.

The primaries, P^1, P^2, P^3, of three transformers are connected between the three lines A, B, C, leading from the generator; and three secondaries, S^1, S^2, S^3, are connected in delta to the three lines, a, b, c, leading to the motor. A recording wattmeter of the three-phase type, for measuring the power consumed by the motor, is shown connected in the system with the field spools at f, the armature circuit a^1 and its resistances r, between the three secondary lines.

Induction motors may be supplied from a three-phase

generator by means of two reducing transformers in the manner shown in Fig. 189. This arrangement (which is the open delta connection) is identical with that in Fig. 188, except that one of the transformers, P^3, S^3, is left out, and the two other transformers are made correspondingly larger. The recording wattmeter is connected in the

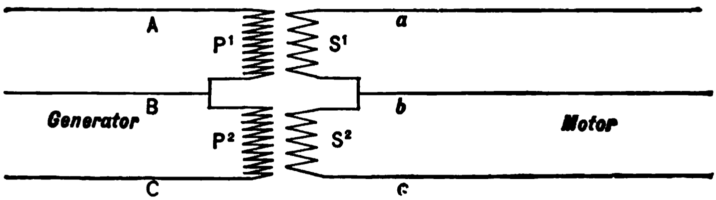


Fig. 189.

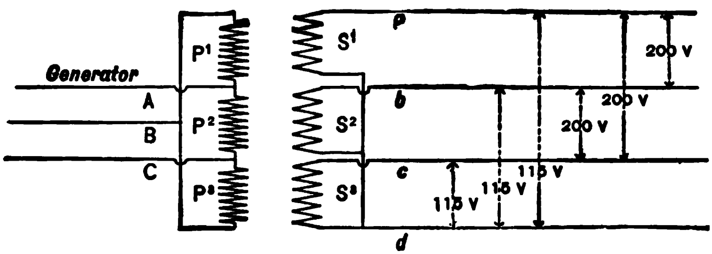


Fig. 190.

secondary circuit in the same way as in the use of three transformers.

The connections of three transformers for a low-tension distribution system, by the three-phase four-wire system, are shown in Fig. 190. The three transformers have their primaries, P^1, P^2, P^3, joined in delta connection, and their secondaries, S^1, S^2, S^3, in Y connection. Lines a, b, c, are the three main three-phase lines, and d is the common neutral. The difference of potential between a

and *b*, *b* and *c*, and *a* and *c* is 200 volts, while that between them and *d* is 115 volts. 200-volt motors are joined to *a*, *b*, and *c*, while 115-volt lamps are connected between *a* and *d*, *b* and *d*, or *c* and *d*. Line *d*, like the neutral wire in the Edison three-wire system, only carries current when the load is unbalanced.

Measurement of Power. — In a *Y*-connected generator the *E.M.F.*, induced in each phase, is $\frac{E}{\sqrt{3}}$, and the energy in that phase is $I \times \frac{E}{\sqrt{3}}$, *E* being the *E.M.F.* at the generator terminals. In a delta-connected generator the current in each phase winding is $\frac{I}{\sqrt{3}}$, *I* being the line current, and the energy is $E \times \frac{I}{\sqrt{3}}$. The total energy for the three phases, in the cases both of a *Y* and a Δ connected generator, is $= \sqrt{3} \times E \times I$. This formula is correct when the generator output is of a non-inductive character. If a phase displacement exists, the expression becomes $\sqrt{3} \times E \times I \times Cos\, \Phi$. These formulas apply equally well for determining the power in a three-phase circuit, irrespective of the method of connections of the supplying source or of the consuming devices.

As an illustration, — the power in a non-inductive three-phase circuit, in each branch of which 100 amperes are flowing, the voltage between lines being 2,500, is found as follows: the energy in each phase is = 100 amperes $\times$ 2,500 volts $\div \sqrt{3}$ = 145 kilowatts, and, for the three circuits, is therefore 435 kilowatts. If the circuit had a power factor of 80 per cent, the energy would then be 435 $\times$ 0.80 = 348 kilowatts.

The power supplied by three-phase circuits can be measured by the use of three, two, or one wattmeter. Three wattmeters will give the power of a circuit irrespective of the condition of balancing or lag. The sum of the readings of the three instruments is the total power. Each wattmeter must be connected to the common center or neutral of the system. If the apparatus is connected delta, it is necessary to make an artificial neutral with resistances. Two wattmeters can be connected so that, as long as the power factor is greater than 50 per cent, the sum of the two readings equals the total power. The difference of the two readings will give the power when the power factor is less than 50. As it is not possible to tell when the power factor falls below this point, without reversing the connections, this method is inconvenient and undesirable.

When three-phase circuits are in balance in respect to load and power factor the power may be measured by one wattmeter. Three times the readings of the single wattmeter will give the total power in the circuits. Figs. 191 and 192 show the connections of three-phase recording wattmeters for a low and for a high voltage circuit. The wattmeter is provided with resistances, r, r and r^1, for creating an artificial neutral. The armature windings are in series with r^1, so that $r^1 + a = r$. The wattmeter, diagrammatically illustrated in Fig. 191, is adapted for circuits of 550 volts and less. Fig. 192 shows the connection of a wattmeter for circuits of from 1,000 to 3,000 volts. Station transformers t and t are required to reduce the pressure for the armature windings.

The connections for an indicating wattmeter are the same as those for a recording wattmeter. The main cur-

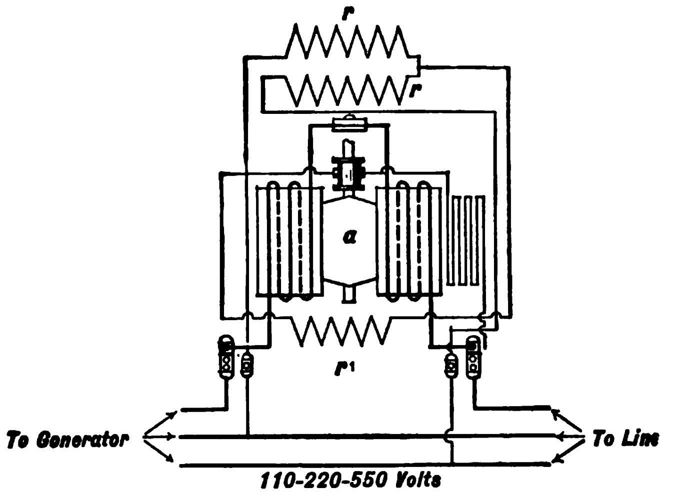


Fig. 191.

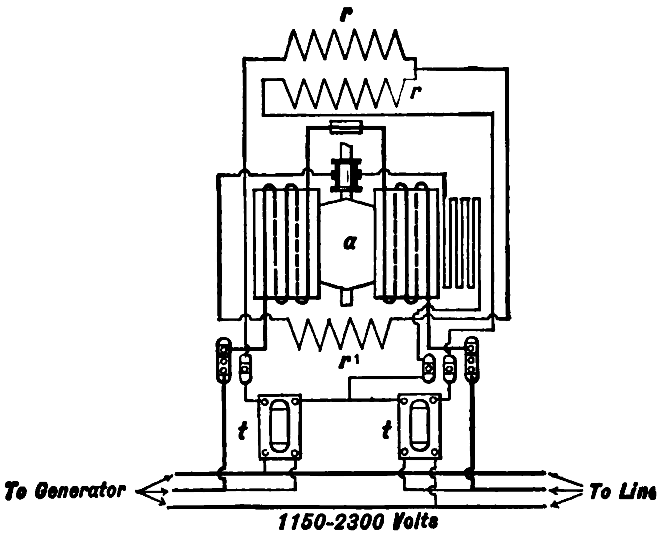


Fig. 192.

rent is taken by the stationary or low-resistance coil, while the pressure coil is of high resistance, and connected to the artificial neutral.

The power in unbalanced three-phase circuits is measured by a special form of wattmeter of the induction type. This wattmeter is also largely used in balanced circuits.

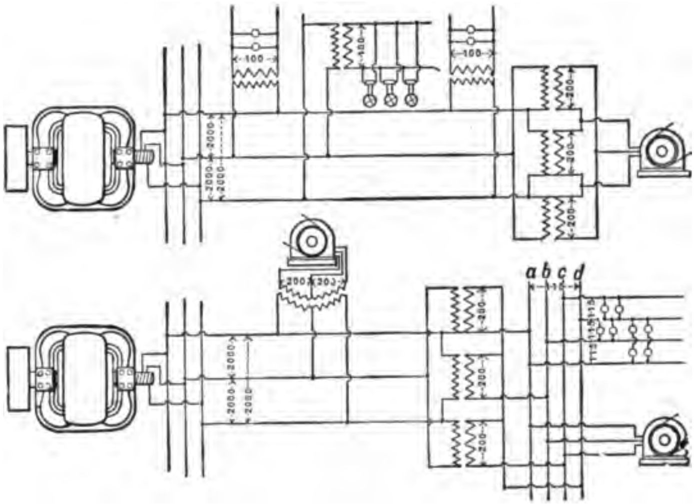


Fig. 193.

Three-Phase Circuits. — The general arrangement of circuits for a local distribution of light and power is shown in Fig. 193. The generators are wound for 2,000 volts, feeding direct into the mains. Step-down transformers reduce the power to 100 volts for lights and 200 volts for motors. In one arrangement alternating inclosed arc lights are shown, operated from a transformer. A 200-volt motor is supplied by three transformers, constituting

a system of secondary mains. In the second arrangement a motor running from two transformers, and a general distributing system, are shown. The general practice is to wind the generators for about 2,200 or 2,300 volts at full load and use transformers reducing to 115 volts for light and small motors. Where secondary mains are employed the motor pressure is 200, 220, 440, or 550 volts.

Where lights and motors are located a considerable distance from the generators, the cost of copper is reduced by employing transformers to raise the current pressure. An arrangement of three-phase circuits for transmitting power over long distances is shown in Fig. 194. The generator, direct-connected to the source of power, a water-wheel, is shown at *A*. *B* is a bank of step-up transformers, raising the voltage to, say, 20,000. As this voltage is higher than can be used with any apparatus for direct utilization of the current, step-down transformers C_1, C_2, and C_3, are required.

The main substation contains the transformers C_1 and C_2. This is a true central or distributing station. From this point the distributing feeders are taken out at, say, 2,000 volts, for the commercial primary circuits and through the bank C_2 at 115 volts, to feed a low-tension network. Through the transformer C_1, a current of 2,000 volts is fed direct into a synchronous motor, and into transformers reducing to 115 volts for supplying motors and lights. The substation transformers C_2 furnish current for a general lighting and motor service at *I*, *J*, and *H*. The voltage for this distributing system is controlled by the regulators *G*.

At C_3 another bank of step-down transformers is located. An alternating current of suitable voltage is delivered to

the rotary converter *D*, which supplies continuous current to the electrolytic vats or storage battery *E*. A rotary

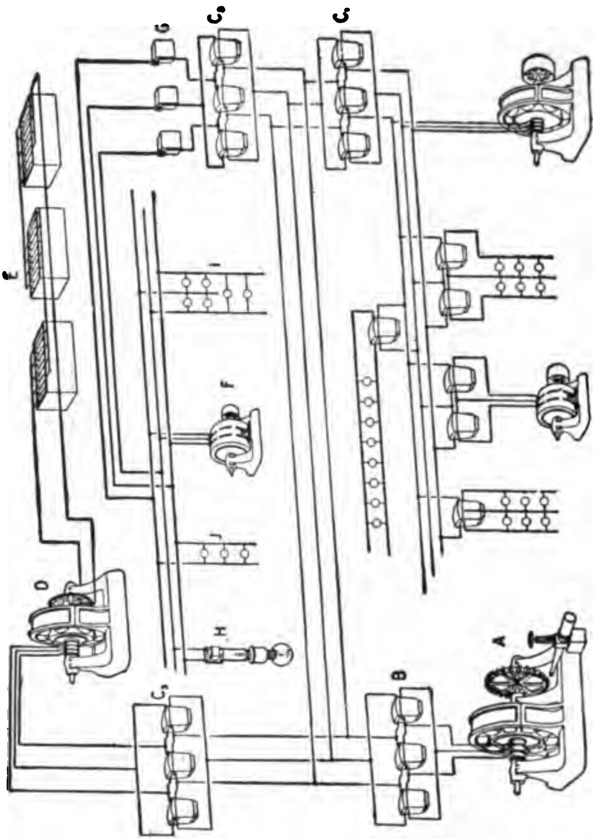


Fig. 194.

converter might also furnish direct current for electric railway service. The arrangement of apparatus in a modern rotary converter substation for railway service has already been illustrated in Figs. 149 and 150.

Three-Phase Lighting Circuits. — For both arc and incandescent lighting by low-tension three-phase distribution, two systems are in use. The first is known as the single-phase three-wire system, the general arrangement and connections of which are shown in diagram 195. The second system is the three-phase four-wire, which has been

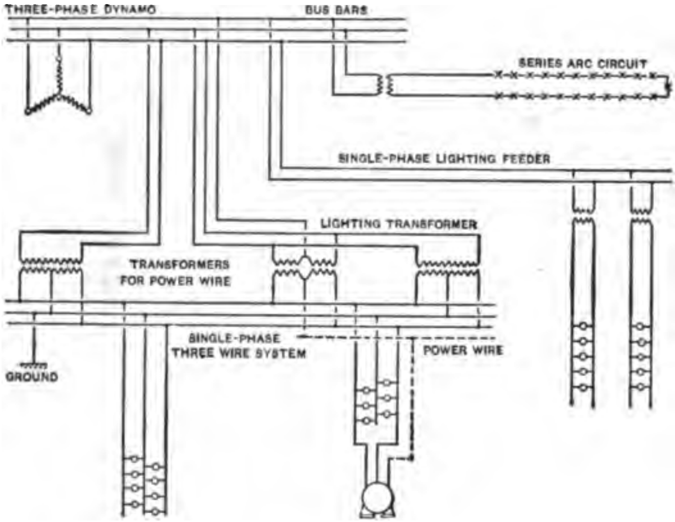


Fig. 195.

described before. The connections of this system for lighting installations are shown in diagram 196.

In the first system the incandescent lighting service is mainly supplied from one circuit of the three-phase generator, and the voltage is regulated with respect to the needs of the three-wire lighting circuit. The primary circuits having a small drop, make it possible to lay out a secondary network having a very superior regulation. When motors

are operated on this system, a separate power wire is required, the connections of which are shown in the diagram.

The advantage of the four-wire three-phase system is that as long as it is balanced, the generator load remains balanced. Another favorable feature is that its outside

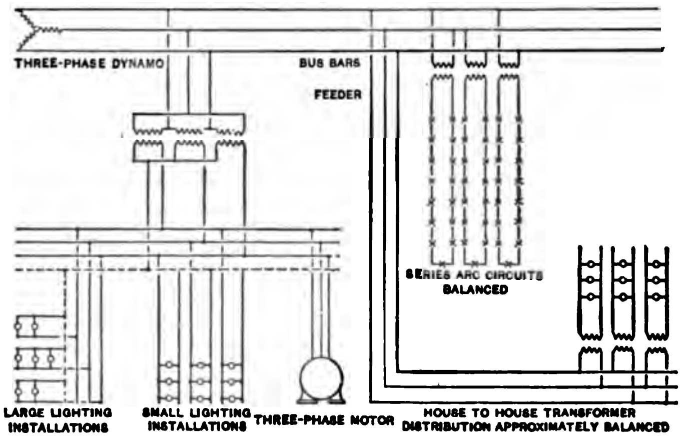


Fig. 196.

wires are available for operating motors. This system is not so desirable in cases where the system may be seriously unbalanced, as by arc lamps or other very inductive load unequally distributed. It is also inferior in simplicity and in facility of voltage regulation to the single-phase three-wire system.

Three-Phase Generators. — The three-phase generator will ordinarily deliver 75 per cent of its rated capacity, in single-phase current, between any two conductors, with the same heating as when delivering full three-phase load.

When running as a single-phaser, or when the load is unbalanced between the conductors, the potential differences of the phases are unequal. The phase carrying the load will have one voltage, while one of the disused or

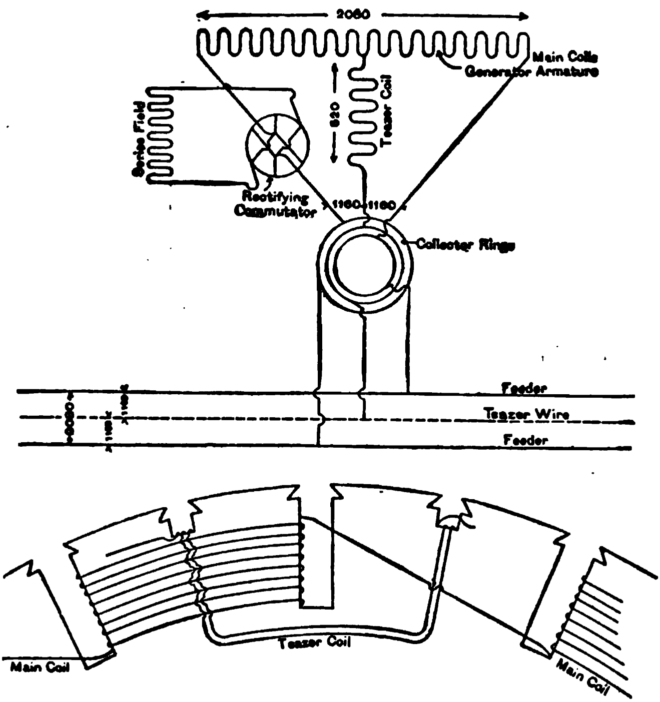


Fig. 197.

lightly loaded phases will have a higher voltage and the other a lower voltage. In machines of good regulation, these differences are small, and can be readily taken care of by regulators in the feeder circuits. These differences are also smoothed out by the use of motors and synchronous

apparatus connected to the three-phases. The unused phases can be loaded with other single-phase currents, thus giving varying degrees of unbalancing, and increasing the load with normal heating, inversely as the unbalancing, up to the total three-phase capacity of the generator. As a three-phase generator, for a given output, is cheaper and smaller than a single-phaser, it will often be found desirable to install a three-phase machine for single-phase working. Intelligent and careful arrangement of the feeder circuits will give the best possible results as to regulation. This is the more easily obtained by the use of regulators, which modern engineering demands shall be installed in every central station.

Monocyclic System. — In the monocyclic system, which was at one time considerably used, the generators are of a special type, having a main single-phase winding and an auxiliary or teaser winding connected to the central point of the main winding and in quadrature therewith. The arrangement of these windings is shown diagrammatically in Fig. 197, which illustrates also the disposition of the main and teaser coils in their respective slots on the armature core. The teaser coil generates a voltage equal to about 25 per cent of that of the main coil, so that the *E.M.F.* between the terminals of the main coil and the free end of the teaser is the resultant of the *E.M.F.* of the two coils, and is shown in magnitude and direction by Fig. 198. By various transformer connections it is possible to resolve this triangle of *E.M.F.* into one that gives

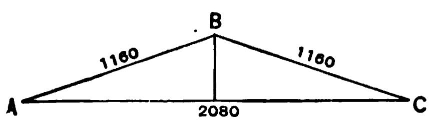


Fig. 198.

a practically correct three-phase relationship for use where polyphase motors are to be used. In this system two wires leading from the ends of the single-phase winding in the generator supply single-phase current to the lighting load, a third wire connected to the end of the teaser being run to points where the polyphase motors are installed.

CHAPTER XIV.

CHOICE OF FREQUENCY.

High Frequencies. — In designing a plant for the distribution of light and power by polyphase currents, one of the first considerations that presents itself is the frequency of the apparatus. Formerly, the frequencies generally employed in the United States were 125 and 133 cycles, or 15,000 and 16,000 alternations. Abroad, the commercial frequencies were somewhat lower, varying from 80 to 100 cycles. The adherence to a high frequency in this country for over ten years resulted in an investment of millions of dollars in this particular type of apparatus, and made the introduction of new types of lower frequency into old and existing central stations somewhat difficult, even when evident economy and advantage were shown to follow upon such introduction.

To-day in the organization of a new plant, the problem is almost invariably confined to the selection of a frequency of 60 cycles or under.

There were frequently strong reasons for retaining or adopting 125 or 133 cycles. One of these has been mentioned above. The change from 125 cycles to a lower frequency necessitated a complete revamping of the installation, and, with the exception of the small sizes, the transformers must be replaced. Again, when a low first-cost of a plant is considered of more importance than a possible

ultimate saving of operating expenses, and a more satisfactory service, a high frequency will be used. The generators are cheaper. The transformers are also smaller and cheaper.

One of the drawbacks to the use of high frequencies, especially in the transmission of power over lines of considerable length, is the drop of voltage due to the reactance of the line, which increases with the frequency. For illustration: the reactance of 1,000 feet of No. 1 wire, at 25 cycles, is 0.0486 ohm, and at 125 cycles, 0.243 ohm.*

By reducing the frequency from 125 cycles to 25 cycles, in the above case, the voltage drop, due to the reactance and resistance, is reduced almost one-half. With heavier conductors and higher frequencies, the difference is still more noticeable. The effect of frequency on the voltage drop in transmission lines is treated at further length in Chapter XVI. In lighting plants employing large conductors, on account of the varying power factors due to changing character of load, the irregularity in voltages at high frequencies may become quite marked. As we have seen, this voltage drop is not all energy loss, this loss being only proportional to the energy component of the total drop.

Other disadvantages in the use of high frequencies are the speed at which both generators and motors must run in order not to unduly increase the number of poles, and the difficulty in connection with engine regulation, when a number of generators are direct driven, and operated in parallel. High-frequency as well as low-frequency induction motors operate better at high speeds, but these are undesirable from both mechanical and commercial stand-

* See Table of Line Constants for Power Transmission, p. 344.

points. On the other hand, high-frequency induction motors of reduced speeds have, as a rule, low power factors. The high-frequency induction motor was introduced to meet the demands for motors of small power on high frequency circuits. With the system on which it is at present operated, it may in time become a thing of the past.

To sum up: High frequencies, i.e., over 60 cycles, permit the use of cheap generators and transformers, and, in addition, the simple and satisfactory operation of incandescent and arc lamps. They have the disadvantage of increasing the voltage drop and idle currents of circuits, with consequent bad regulation and the heating of the generator at light loads, of not permitting the parallel operation of direct-connected machines of low speed, and the further disadvantage, that induction motors must either run at excessive speeds or with poor power factors. Synchronous motors will not start with the same vigor as on lower frequencies.

Low Frequencies. — Up to the present time no arc lamp has been made that will operate with entire satisfaction on frequencies of less than 40 cycles. Incandescent lamps cannot be used to advantage on frequencies less than 30 cycles. Low-voltage incandescent lamps show no flicker; but the effect of fatiguing the eye is noticeable at 25 cycles, especially in high-voltage lamps.

Transformers are somewhat bulkier, more expensive, and slightly less efficient at low frequencies. Induction motors, while likewise larger and more expensive, as a rule can be built with equal, if not better, power factors, and at convenient and commercial speeds. Rotary converters can be successfully designed for 60 cycles. The speed is high,

however, and the best mechanical and electrical results are obtained at frequencies under 40 cycles. The largest use of miscellaneous power by rotary converters is at Niagara, where a frequency of 25 cycles is employed.

The Niagara plant is essentially a power plant. The use of current for both arc and incandescent lighting is of no great importance. The power, electrically generated on a scale never before attempted, is used locally in a great variety of processes, and is delivered in a form most suitable for its diverse uses. Power by the direct-current system, while convenient for some particular operations, would not answer equally well all requirements at Niagara, and would be unsuitable for long-distance transmission. A high-frequency system would restrict the use of motors and rotary converters, and the transmission of power over very long distances. Sixty and 40 cycles, however, permitting the general use of lighting apparatus, do not give the best results with rotary converters of large output. The operation of 25-cycle rotary converters, on the scale employed at Niagara, shows that, for the purely power conditions there existing, this frequency was wisely chosen.

A frequency of 25 cycles is also used by the Brooklyn Edison Illuminating Company in the extension of their plant. The power is transmitted within an area covering 75 miles, to various substations, where 25-cycle rotary converters are stationed. These deliver 115 volt direct-current into Edison three-wire mains. The Chicago Edison Company use a somewhat similar system of distribution and the same frequency.

For the general conditions of a power plant, supplying alternating current for induction motors and lighting, and making a specialty of furnishing direct current on a

large scale, at some distance from the generating plant, a frequency of less than 40 cycles will be found suitable.

The frequency of 60 cycles, or 7,200 alternations per minute, has come into extensive use. In Europe the frequency of 50 cycles is more used than any other. These frequencies have the advantage of considerably reducing line reactance and the idle currents present in lighting systems of higher frequencies. They are adapted for the most economical results in a general distributing system of lights and motors. On account of the good regulation possible with these frequencies the highest economy lamps can be used. The motors are excellent in respect to efficiency and power factor, and run at commercial speeds. Both motors and transformers are reasonable in cost.

When the generating units are direct connected to engines of extremely slow speed and operated in parallel, a frequency of 50 or 60 cycles will be found to be not desirable. As explained in Chapter III, the permissible variation in rotative speed is not so great as with lower-frequency generating units.

Choice of Frequency. — It is impossible to make more than the most general application of the foregoing remarks. Each particular case must be studied in the light of its special conditions, before an intelligent decision can be made as to the proper frequency to employ. At the risk of repetition, the following general recommendations are suggested as embodying the latest and standard practice:

For local lighting systems with incidental demand for power in small units, where old transformers have to be retained, and where a cheap plant is of first consideration, a high frequency may be used, but should be discouraged as much as possible.

For local transmission and distribution for lighting and power purposes, conditions which accompany the majority of alternating-current propositions, a standard frequency of 60 cycles can be used to advantage.

In power and lighting plants, supplying current to induction motors and to rotary converters, and for lighting, and, finally, for very long transmissions of power, a frequency of 50 cycles, or thereabouts, may be used. This is a good, all-round frequency, and is coming into more general use. It is much employed abroad.

For exclusively power plants, where lighting is of no importance whatsoever, and where rotary converters and motors of large size or slow speed are to be supplied, a frequency of 25 to 30 cycles may be used.

Notwithstanding the opportunity for the careful exercise of judgment in selecting a proper frequency, almost equally good results can be obtained with widely different frequencies. As an illustration, the Brooklyn Edison Company have adopted 25 cycles for their power and rotary converter work. The Boston Edison Company obtain practically the same results, using a frequency of 60 cycles. Power is transmitted over the 150 miles of line of the Bay Counties Company in California at a frequency of 60 cycles. The 100 mile transmission of the Government of Mysore, India, is accomplished at a frequency of 25 cycles.

CHAPTER XV.

RELATIVE WEIGHTS OF COPPER FOR VARIOUS SYSTEMS.

As the transmission and distribution of power often involves a large outlay for copper conductors, it is most important to ascertain what system and what combination of conductors will give the most economical results. In making any comparison between the copper efficiencies of the various systems, the proper basis of comparison is equality of voltage.

The amount of copper required for transmitting a given power at a fixed percentage loss is found by the rule that the weight of copper varies inversely as the square of the voltage.

The voltage of an alternating circuit, as measured by the ordinary commercial instruments, — i.e., the effective voltage, — is about 30 per cent less than the maximum value of the *E.M.F.* wave. It is this maximum value that must be considered in determining the break-down point of insulation and the highest voltage that can be used commercially, as in the long-distance transmission of power. On the other hand, when the maximum voltage of a circuit is within the limit of safe insulation strain, the effective voltage carries no limitation with it.

The comparison, then, of the various systems, to determine the most economical method of transmission, will be

either on the basis of maximum potential, as in the case of long transmission lines, or on the basis of effective or minimum potential, as in the case of low-potential distributions by secondary mains.

Figs. 199 to 204 show the standard systems of alternating-current distribution and the various combinations of conductors in general use. The name of each system is given, and also the relative amount of copper required.

The relative amount of copper required by the single-phase system, which is here taken as the standard of comparison for the other systems and combinations, is illustated by diagram (Fig. 199). The single-phase three-wire system is shown in Fig. 200. If the voltage of the two-wire system is e, the potential between the two outside wires is $2e$. Applying the rule that the amount of copper is inversely as the square of the voltage, only $\frac{1}{4}$ the copper would be needed, if the neutral should have no cross section, or the return conductor be dispensed with, as might be done in the case of a perfect balance. If the neutral is given a cross section equal to one of the outside wires, the total copper in the three-wire single-phase system is 37.5 per cent that of the two-wire single-phase system. With a neutral $\frac{1}{2}$ and $\frac{1}{3}$ the cross section of the outside wires, the total copper is 31.25 per cent and 29.15 per cent respectively of our standard system. In a four-wire single-phase system the voltage between outside wires is $3e$, and, under perfect balance, $\frac{1}{9}$ the amount of copper would be required. When the neutral and outside wires are of equal size, the copper must be increased to 22.2 per cent. In like manner the copper in the five-wire system, with neutrals of full cross section, is 15.62 per cent, and the same system, with neutrals of $\frac{1}{2}$ the area of the neutral wires, requiring only 10.93

SYSTEM | *WIRING CONNECTIONS* | *PER CENT. COPPER* | *DIAGRAM*

Single Phase 2 Wire

Fig. 199.

100.

Single Phase 3 Wire

Fig. 200.

37.5

Two Phase 4 Wire

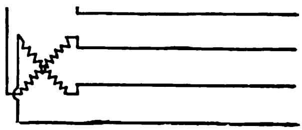
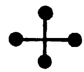


Fig. 201.

100.



Two Phase 3 Wire

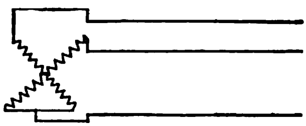
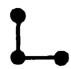


Fig. 202.

{145.7 72.9



Three Phase 3 Wire

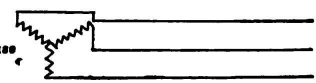
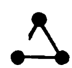


Fig. 203.

75.



Three Phase 4 Wire

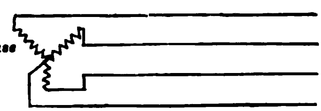
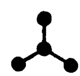


Fig. 204.

33.3



per cent of the copper of the simple alternating circuit. These results are the same whether the comparison is made on the basis of maximum potential, or on the basis of effective or minimum potential.

In the three-phase system, the copper required for cer-

tain given conditions is 75 per cent of the copper used in the single-phase system. The comparison between polyphase systems can best be made by resolving each into as many single-phase systems as it has phases. The three-phase system consists of three single circuits with a common ground, or, what is the same, with no return; for the total current to and from the centre is zero. If the Δ or line voltage is e (Fig. 203), the pressure or volts between any wire and the juncture is $\frac{e}{\sqrt{3}}$. The single-phase system, having a line voltage e, can also be converted into two single circuits of voltage $\frac{e}{2}$ (Fig. 201). As the weight of copper in each system is inversely as the square of the voltage, we have: $\left(\frac{2}{e}\right)^2 : \left(\frac{\sqrt{3}}{e}\right)^2 = 4:3$ — or the relative amounts of copper, for the single-phase and the three-phase systems, are 100 per cent and 75 per cent. Now the two-phase four-wire system, consisting of two single-phase systems, is placed, in respect to the amount of copper required for equal conditions, in the same position as the single-phase system. Therefore the relative amounts of copper for the two-phase and three-phase systems are 100 per cent and 75 per cent.

Fig. 202 illustrates the two-phase three-wire distribution, two of the wires of the four-wire system being replaced by one of full cross section. The voltage between the two outside conductors is now raised to $e\sqrt{2} = 1.414\ e$, e being the potential between the conductors of either phase. The amount of copper required, when compared with the single-phase system, will differ considerably according as the comparison is based on the highest voltage permissible for any given distribution, or on the minimum voltage for

low-tension service. If e is the maximum voltage that can be used on account of the insulation strain, or for any other reason, the pressure between the other conductors of the two-phase three-wire system must be reduced to $\frac{e}{\sqrt{2}}$. The weight of copper required under this condition is 145.7 per cent of the single-phase copper. If the limiting conditions of voltage do not exist, a comparison of the relative weights of copper can be made with the effective voltage of either phase as a basis, — i.e., on a basis of the minimum voltage. In this case we find a relative saving over the single-phase circuit of about 27 per cent, the actual amount of copper being 72.9 per cent of the single-phase conductors.

Fig. 204 shows the connections of the three-phase four-wire system. When the fourth wire, or neutral, is of full cross section, the copper required is $33\frac{1}{3}$ per cent of the single-phase system. By making the neutral one-half the cross section of the main conductors, the copper weight is reduced to 29.17 per cent. This arrangement is only used for secondary systems of distribution, as described before. The comparison with any other system is, therefore, made only on a basis of equality between phases of minimum voltage.

The following Tables are compiled from data in Mr. Steinmetz's valuable work, "Alternating-Current Phenomena." The first Table gives the relative copper efficiencies of various systems, when the comparison is on the basis of equality of minimum difference of potential. The second gives the relative weights, when the comparison is based on the equality of the maximum potential difference in the system.

Amount of copper required for transmission at a given loss, based on minimum potential.

System.	No. of Wires.	Per Cent Copper.
Single-phase	2	100.
Single-phase	3	37.5
Two-phase, common return	3	72.9
Two-phase	4	100.
Three-phase	3	75.
Three-phase, neutral full section . . .	4	33.3
Three-phase, neutral one-half section .	4	29.17

Amount of copper required for transmission at a given loss, based on maximum difference of potential.

System.	No. of Wires.	Per Cent Copper.
Single-phase	2	100.
Two-phase, with common return . . .	3	145.7
Two-phase	4	100.
Three-phase	3	75.
Direct Current	2	50.

It will be seen that the direct-current system requires only 50 per cent of the copper in the single-phase system when used in long-distance transmission of power. The advantage is not so evident, however; for, as Mr. Steinmetz has pointed out, in addition to the electrostatic stress, an electrolytic effect is set up, which does not exist to the same extent in alternating currents. The complications attending the utilization of direct current of high tension, are such that, with the exception of a few special cases, its employment in the long-distance transmission of power has not been considered practicable.

CHAPTER XVI.

CALCULATION OF TRANSMISSION LINES.

Line Constants.—As explained in Chapter I., the drop of voltage in an alternating-current circuit will vary with the resistance and the reactance of the circuit, and with the character of the load. In the table, "Line Constants for Power Transmission," taken from a publication of the General Electric Company, the relation of reactance to resistance is shown for a number of frequencies, and for the sizes of conductors ordinarily used in power transmissions, and also other constants of transmission circuits, such as capacity, inductance, and charging current. The following explanations will serve to make the table clear:

The *E.M.F.* consumed by resistance r, of the line, is $= Ir$, and in phase with the current I.

The *E.M.F.* consumed by the reactance, S, of the line, is $= IS$, and in quadrature with the current I.

The *E.M.F.* consumed in the line is neither Ir nor IS, but depends upon the phase relation of current in the receiving circuit.

The loss of energy in the line is $= I^2r$, hence does not depend upon the reactance, but only upon the resistance.

Two wires in parallel have the same resistance, and about half the reactance (if strung on separate insulators and intermixed) of a single wire of double cross section. Thus replacing one No. 0000 wire by two No. 0 wires, the resistance, weight

of copper, etc., will remain the same, but the reactance will be reduced practically to half, so where lower reactance is desired, the use of several conductors strung on independent insulators and intermixed is advisable.

The values given for *L*, *C*, *i*, and *S* are calculated for sine-waves of current and *E.M.F.*

This table will be found most convenient for determining the characteristics of transmission circuits when the size of conductor has been fixed. The conductors are assumed to be separated by a distance of 18 inches.

Let us take, as an example, a case where it is required to deliver, by the three-phase 60 cycle system, 2,000 H.P. at the secondary terminals of the step-down transformers, over a circuit 11 miles in length. It is further assumed that the voltage at the receiving end is 10,000, and the total energy loss in transmission from the generator terminals is not to exceed 10 per cent. The power is to be used for a mixed system of lights and induction motors, the latter forming most of the load. The power factor of the system at the receiving end will be approximately 85 per cent. We can assume that —

The transformers have an efficiency of $97\frac{1}{2}$ per cent.
The copper loss in each being 1 per cent.
The core or hysteresis loss, $1\frac{1}{2}$ per cent.
The reactance can be taken as $3\frac{1}{2}$ per cent.
And the magnetizing current 4 per cent.

The voltage between any branch of the circuit and the common centre of the system is

$$\frac{10,000}{\sqrt{3}} = 5,775.$$

The energy delivered by each branch is

$$\frac{1,500}{3} \text{ K.W.} = 500 \text{ K.W.}$$

The apparent energy delivered by each branch is

$$\frac{500}{0.85} = 588 \text{ K.W.}$$

The total current in each branch is $\frac{588,000}{5,775} = 102$ amperes.

The *I.R.* drop in each branch is 10 per cent of $5,775 = 577.5$ volts.

The total resistance $R = \frac{577.5}{102} = 5.66$ ohms.

The resistance of one mile is $\frac{5.66}{11} = 0.514$ ohm, which is very nearly the resistance of No. 0 wire. Three No. 0 wires, therefore, will carry 2,000 H.P. a distance of 11 miles with a waste of energy of 10 per cent, the pressure at the receiving end being 10,000 volts and power factor 85 per cent.

By referring to the table the characteristics of this transmission line are readily obtained. The reactance of eleven miles of single conductor is seen to be 6.62 ohms at the frequency employed. The inductance, or what is the same thing, the coefficient of self-induction of the line, is 17.6 millihenrys. The charging current of each line for the eleven miles, with the given voltage and frequency, is found to be 0.4 ampere.

It is interesting to know what the impressed or generator *E.M.F.* and the distribution of current will be, in this case, when the plant is fully loaded. For this investigation, the entire system may be reduced to a uniform voltage, by multiplying the voltages by the various ratios of transformation, thus bringing both the secondary pressure at the step-down transformers, and the generator pressure, to the line voltage. The current values are, of course, inversely changed. The power factor of the load, having been assumed as 0.85, the induction factor will be $\sqrt{1-(0.85)^2} = 0.52$.

Line Constants for Power Transmission.

Per 1,000 Feet of Wire B. & S. G.

Size of Wire.	Weight.	Diameter.	Area in Circular Mils.	Resistance at 75° F.	Inductance in Millihenrys.	Capacity in Microfarads.	Charging Current.	Reactance at 25, 40, 60, 125 Cycles. in Ohms.				Size of Wire.
No.	Lbs.	Mils.	*C.M.*	r	L	K	i_0	S_{25}	S_{40}	S_{60}	S_{125}	No.
0000	630	460	211,600	.049	.282	.00388	.0244	.0443	.0708	.1062	.221	0000
000	507	410	167,805	.062	.290	.00378	.0238	.0455	.0727	.1090	.227	000
00	402	365	133,079	.078	.296	.00368	.0232	.0465	.0743	.1113	.232	00
0	319	325	105,592	.098	.303	.00358	.0226	.0476	.0761	.1141	.238	0
1	253	289	83,694	.124	.310	.00351	.0220	.0486	.0775	.1166	.243	1
2	201	258	66,373	.156	.317	.00342	.0215	.0498	.0796	.1194	.249	2
3	159	229	52,633	.197	.324	.00334	.0210	.0509	.0814	.1220	.254	3
4	126	204	41,742	.249	.332	.00326	.0205	.0521	.0832	.1248	.261	4
5	100	182	33,102	.314	.339	.00320	.0201	.0532	.0850	.1277	.266	5
6	79	162	26,250	.395	.346	.00313	.0197	.0543	.0867	.1301	.271	6
7	63	144	20,816	.499	.352	.00306	.0193	.0553	.0885	.1327	.276	7
8	50	128	16,509	.629	.360	.00300	.0189	.0565	.0904	.1355	.283	8
9	40	114	13,094	.792	.366	.00294	.0185	.0575	.0920	.1380	.288	9
10	31	102	10,382	.999	.373	.00288	.0181	.0585	.0936	.1405	.293	10

Per 1,000 Feet of Wire B. & S. G.

PER MILE OF WIRE B. & S. G.													
0000	3,376	460	211,600	.26	1.489	.02046	.1286	.234	.374	.561	1.167	0000	
000	2,677	410	167,805	.33	1.529	.01993	.1255	.240	.384	.576	1.199	000	
00	2,123	365	133,079	.41	1.562	.01943	.1223	.245	.392	.588	1.225	00	
0	1,685	325	105,529	.52	1.600	.01892	.1191	.251	.402	.602	1.257	0	
1	1,335	289	83,694	.65	1.636	.01854	.1163	.257	.409	.616	1.283	1	
2	1,059	258	66,373	.83	1.674	.01806	.1135	.263	.420	.630	1.314	2	
3	840	229	52,633	1.04	1.711	.01765	.1110	.269	.430	.644	1.343	3	
4	666	204	41,742	1.31	1.750	.01722	.1085	.275	.439	.659	1.379	4	
5	528	182	33,102	1.66	1.788	.01689	.1060	.281	.449	.674	1.403	5	
6	419	162	26,250	2.09	1.826	.01651	.1038	.287	.458	.687	1.431	6	
7	332	144	20,816	2.63	1.860	.01617	.1018	.292	.467	.701	1.459	7	
8	263	128	16,509	3.32	1.901	.01584	.0997	.298	.477	.715	1.492	8	
9	209	114	13,094	4.18	1.934	.01552	.0977	.304	.486	.729	1.519	9	
10	166	102	10,382	5.28	1.968	.01521	.0956	.309	.494	.742	1.544	10	PER MILE OF WIRE B. & S. G.

r = Ohmic resistance.
L = Inductance in millihenrys per 1,000 feet of conductor.
K = Capacity in microfarads per 1,000 feet of conductor.
i_o = Charging current at 100 cycles and 10,000 volts to neutral, that is, in a 20,000 volt single-phrase, and a 17,300 volt three-phrase line.
$i_o = 2 \times \pi \times$ frequency $\times K \times E \times 10^{-6}$; where E is the $E.M.F.$ between a line and neutral.
S = reactance $= 2 \times \pi \times$ frequency $\times L \times 10^{-3}$.

In Chapter I., it has been shown that the impressed *E.M.F.* is made up of two component parts, one in phase with the current and called the energy component of the *E.M.F.*, the other in quadrature with the current and called the induction component. In symbols:

Impressed *E.M.F.*

$$= \sqrt{\Sigma\,(\text{Energy comp.})^2 + \Sigma\,(\text{Ind. comp.})^2}$$

To obtain the total *E.M.F.* it is necessary, then, to calculate separately all the energy and induction components of the circuit, and obtain a combined resultant.

With the values already assumed, and consulting the preceding table, we obtain the following results:

Circuit.	Voltage. Energy Component.	Voltage. Ind. Component.	Current Amperes.
Secondary Circuit.			
Energy Component, .85 × 5,775,	4,909		
Induction Component, .52 × 5,775,		3,003	
Current,			102
Step-down Transformers.			
Resistance loss = *I.R.* = 1% of 5,775,	58		
Reactance loss = *I.S.* = 3½% of 5,775,		202	
Hysteresis loss = 1½% of 102,			1.5
	4,967	3,205	103.5
Line.			
Resistance loss = *I.R.* = 103.5 × 5.72,	592		
Reactance loss = *I.S.* = 103.5 × 6.62,		685	
$\sqrt{(5{,}559)^2 + (3{,}890)^2} = 6{,}785$ = volts at terminals of step-up transformers.	5,559	3,890	103.5
Step-up Transformers.			
Resistance loss = *I.R.* = 1% of 6,785,	68		
Reactance loss = *I.S.* = 3½% of 6,785,		238	
Hysteresis loss = 1½% of 103.5,			1.5
$\sqrt{(5{,}628)^2 + (4{,}128)^2} = 6{,}980$ = volts at generator.	5,627	4,128	105.

The energy *E.M.F.* between any one line and the neutral at the generator end is seen to be 5,627, and the volts consumed by the reactance of the system, 4,128. The total volts required at the generator terminals are found to be 121 per cent of the voltage at the secondaries of the transformers, reduced to the line voltage, — i.e., with 10,000 equivalent volts between the lines at the transformer secondaries, the pressure at the generator must be 12,100 volts. The current delivered by the generator to the line is 105 amperes, and is 3 per cent more than the current in the secondary circuits. The effect of the transformer core losses is the same as if a corresponding current was consumed by lamps or other apparatus connected across the mains. The volt-ampere output of the generator is 125 per cent of the apparent watts at the receiving end. The power factor of the entire system is found to be about 80 per cent.

Simple Wiring Formulas.— A simple and sufficiently accurate determination of the sizes of conductors, voltage drop, and distribution of currents, in any direct or alternating-current system, can be made from the general formula based on Ohm's law, modified by the use of the proper constants. The former formula and constants will be found especially useful and convenient for this calculation:

$$\text{Area of conductor, Circular Mils} = \frac{D \times W}{P \times E^2} \times K$$

$$\text{Volts loss in lines} = \frac{P \times E}{100} \times M$$

$$\text{Current in main conductors} = \frac{W}{E} \times T$$

D = Distance of transmission (one way) in feet.

W = Total watts delivered to consumer.

P = Per cent loss in line of W.

E = Voltage between main conductors at receiving or consumer's end of circuit.

System.	Values of K.					Values of T.			
	Per cent power factor.					Per cent power factor.			
	100	95	90	85	80	95	90	85	80
Single-phase .	2,160	2,400	2,660	3,000	3,380	1.052	1.111	1.176	1.250
Two-phase (4-wire) . . .	1,080	1,200	1,330	1,500	1,690	.526	.555	.588	.625
Three - phase (3-wire) . .	1,080	1,200	1,330	1,500	1,690	.607	.642	.679	.725

Values of the constant, *K*, for any particular power factor are obtained by dividing 2,160 by the square of that power factor for single-phase, and by twice the square of that power factor for three-wire three-phase or four-wire two-phase. The resistance of line wire is taken as 10.8 ohms per mil foot.

T is a variable, depending on the system and nature of the load, and equal to 1 for continuous current, and for alternating current with 100 per cent power factor. Its value for two-phase and three-phase systems is 0.50 and 0.58 respectively, with 100 per cent power factor.

M is a variable, depending on the size of wire, frequency, and power factor. It is equal to 1 for continuous current, and for alternating current with 100 per cent power factor and sizes of wire given in the following table of wiring constants.

The values of *M*, as given in the table, are empirical. They are sufficiently accurate for all practical purposes, provided the displacement in phase between current and *E. M. F.* at the receiving end is not very much greater than that at the generator; in other words, provided that reactance of the line is not excessively large, or the line loss unusually high. For example, the constants should not be

applied at 125 cycles if the largest-size conductors were used, and the loss 20 per cent or more of the power delivered. At lower frequencies, however, the constants are reasonably correct, even under such extreme conditions. They represent about the true values at 10 per cent line loss, are close enough at all losses less than 10 per cent, and often, at least for frequencies up to 40 cycles, close enough for even much larger losses.

In using the above formulas and constants, it should be particularly observed that P stands for the per cent loss in the line of the *delivered power*, and not for the per cent loss in line of the power at the generator.

No. of Wire B. & S. G.	Area Circular Mils.	Weight of Bare Wire per 1,000 ft. Pounds.	Values of M.								
			30 Cycles.			60 Cycles.			125 Cycles.		
			Lighting Only. 98% P.F.	Motors and Lights. 85% P.F.	Motors Only. 80% P.F.	Lighting Only. 95% P.F.	Motors and Lights. 85% P.F.	Motors Only. 80% P.F.	Lighting Only. 95% P.F.	Motors and Lights. 85% P.F.	Motors Only. 80% P.F.
0000	211,600	640.73	1.26	1.27	1.24	1.64	1.85	1.85	2.44	3.06	3.14
000	167,805	508.12	1.20	1.17	1.14	1.49	1.63	1.62	2.15	2.62	2.67
00	133,079	402.97	1.15	1.08	1.05	1.39	1.46	1.42	1.92	2.25	2.29
0	105,592	319.74	1.10	1.00	1.00	1.30	1.32	1.28	1.73	1.96	1.99
1	83,694	253.43	1.06	1.00	1.00	1.23	1.21	1.16	1.57	1.74	1.73
2	66,373	200.98	1.03	1.00	1.00	1.16	1.11	1.06	1.44	1.54	1.53
3	52,633	159.38	1.02	1.00	1.00	1.11	1.04	1.00	1.35	1.38	1.38
4	41,742	126.40	1.00	1.00	1.00	1.07	1.00	1.00	1.26	1.26	1.22
5	33,102	100.23	1.00	1.00	1.00	1.04	1.00	1.00	1.19	1.16	1.11
6	26,250	79.49	1.00	1.00	1.00	1.02	1.00	1.00	1.14	1.08	1.03
7	20,816	63.03	1.00	1.00	1.00	1.00	1.00	1.00	1.09	1.01	1.00
8	16,509	49.99	1.00	1.00	1.00	1.00	1.00	1.00	1.06	1.00	1.00

APPLICATION OF FORMULAS.

SINGLE-PHASE SYSTEM.—125 CYCLES.

EXAMPLE: 750 52-volt lamps, consuming a total of 45,000 watts. Ratio of transformation 20 to 1. Distance to generator, 2,500 feet. Loss in secondary wiring, 2 volts. Voltage drop in transformers, 2 per cent. Energy loss in line, 5 per cent of delivered power. Efficiency of transformers, 97½ per cent.

Watts at transformer primaries

$$= \frac{45{,}000}{0.98 \times 0.97\frac{1}{2}} = 47{,}100.$$

Volts at transformer primaries

$$= (52 + 2) \times 20 \times 1.02 = 1{,}101.6.$$

$$C.M. = \frac{D \times W}{P \times E^2} \times K = \frac{2{,}500 \times 47{,}100 \times 2{,}400}{5 \times (1{,}101.6)^2} = 46{,}500\ C.M.$$

Next larger B. & S. wire

$$= \text{No. } 3 = 52{,}633\ C.M.$$

Loss of delivered power using No. 4 wire

$$= \frac{2{,}500 \times 47{,}100 \times 2{,}400}{52{,}633 \times (1{,}101.6)^2} = 4.4 \text{ per cent.}$$

Total volts lost in line

$$= \frac{P \times E}{100} \times M = \frac{4.4 \times 1{,}101.6 \times 1.35}{100} = 65.5.$$

Generator voltage $= 1{,}101.6 + 65.5 = 1{,}167.1.$

In a 60 cycle single-phase system, with the same conditions as in the above example, the values will be the same, with the exception of the volts lost in the line.

$$\frac{4.4 \times 1{,}101.6 \times 1.11}{100} = 53.8 = \text{volts lost in line.}$$

$1{,}101.6 + 53.8 = 1{,}155.4 =$ generator voltage.

TWO–PHASE SYSTEM. — 60 CYCLES. FOUR–WIRE TRANSMISSION.

EXAMPLE: 2,500 H.P. delivered, 5 miles, at secondaries of step-down transformers. Pressure between lines at receiving end, 6,000 volts. Energy loss in line and in step-down transformers (no step-up transformers), 10 per cent of delivered power. Efficiency of transformers, 97.5 per cent. Power factor of load, 80 per cent. Find size of conductors and voltage drop in transmission line.

Power delivered at step-down primaries.

$$= \frac{2{,}500}{0.975} = 2{,}564 \text{ H.P.} = 1{,}912.7 \text{ K.W.}$$

Energy loss in line = 7.5 per cent.

$$C.M. = \frac{5{,}280 \times 5 \times 1{,}912{,}700}{7.5 \times (6{,}000)^2} \times 1{,}690 = 315{,}940 \ C.M.$$

Three No. 0 B. & S. wires have an area of 316,776 *C.M.* The energy loss, using 3 of this size in parallel, making a total of 12 No. 0 B. & S. wires in all, is:

$$\frac{5{,}280 \times 5 \times 1{,}912{,}700}{316{,}776 \times (6{,}000)^2} \times 1{,}690 = 7.48 \text{ per cent.}$$

Power lost in line

$$= 2{,}564 \times 0.0748 = 195.8 \text{ H.P.}$$

Volts lost in line

$$= \frac{P \times E}{100} \times M = \frac{7.48 \times 6{,}000 \times 1.28}{100} = 574.$$

∴ Generator voltage = 6,574.

Current in line

$$= \frac{W}{E} \times T = \frac{1{,}912{,}700}{6{,}000} \times .625 = 199 \text{ amperes.}$$

The current is, in fact, slightly greater, as no account has been taken of the hysteresis current in the transformers. This will increase the above result about $1\frac{1}{2}$ per cent.

THREE-PHASE SYSTEM. — 60 CYCLES. THREE-WIRE TRANSMISSION.

EXAMPLE: Same conditions as preceding. Find size of conductors and voltage drop in transmission lines.

Power delivered to transformers

$$= \frac{2,500}{0.975} = 2,564 \text{ H.P.} = 1,912.7 \text{ K.W.}$$

Energy loss in line = $7\frac{1}{2}$ per cent.

$$C.M. = \frac{5,280 \times 5 \times 1,912,700}{7.5 \times (6,000)^2} \times 1,690 = 315,940 \; C.M.$$

Three No. 0 B. & S. wires have an area of 316,776 *C.M.*

For the three branches of the three-phase system 9 wires will be required.

$$\text{Energy loss is} = \frac{5,280 \times 5 \times 1,912,700}{316,776 \times (6,000)^2} \times 1,690 = 7.48 \text{ per cent.}$$

Power loss in line

$$= 2,564 \times 0.0748 = 195.8 \text{ H.P.}$$

Voltage drop in line

$$= \frac{7.48 \times 6,000 \times 1.28}{100} = 574.$$

$\therefore$ Generator voltage = 6,574.

Current in line

$$= \frac{1,912,700}{6,000} \times 0.725 = 233.9 \text{ amperes.}$$

The hysteresis current will increase this result by about $1\frac{1}{2}$ per cent.

THREE-PHASE SYSTEM. — 60 CYCLES. FOUR-WIRE SECONDARY.

EXAMPLE: Required, the size of conductors from transformers to the distributing centre of a four-wire secondary system for lights and motors. The load consists of four

15 H.P., 200 volt induction motors, and 750 half-ampere 15 c.p., 115 volt lamps. Length of secondary wiring from transformers to distribution centre, 600 feet. About 15 volts drop on lighting circuits from transformers to distributing centre. Efficiency of motors, 85 per cent. Five volts drop on circuits from distributing centre to motors. Voltage at distributing point between main lines is 205

Current in main lines for motors is

$$\frac{4 \times 15 \times 746 \times 0.725}{0.85 \times 200} = 191 \text{ amperes.}$$

Current from transformers for lamps is

$$\frac{(750 \times 0.5 \times 115) \times 0.607}{200} = 131 \text{ amperes.}$$

Total current from transformers is

$$131 + 191 = 322 \text{ amperes.}$$

For motors,

$$191 = \frac{W}{205} \times 0.725. \quad W = 54{,}000.$$

For lamps,

$$131 = \frac{W}{205} \times 0.607. \quad W = 44{,}240. \quad \text{Total watts} = 98{,}240.$$

Taking for trial two No. 0 B. & S. wires in parallel for each of the main conductors as preferable to one No. 0000, then

$$P = \frac{600 \times 98{,}240}{2 \times 105{,}592 \times 205^2} \times$$

$$\frac{1{,}200 \times 44{,}240 + 1{,}690 \times 54{,}000}{98{,}240} = 9.75.$$

Volts loss in lines

$$= \frac{9.75 \times 205 \times 1.32}{100} = 26.4.$$

Volts at transformers between main lines = 231.4.

Actual drop between main conductors and neutral to distributing point

$$= 26.4 \times \frac{115}{200} = 15.2 \text{ volts.}$$

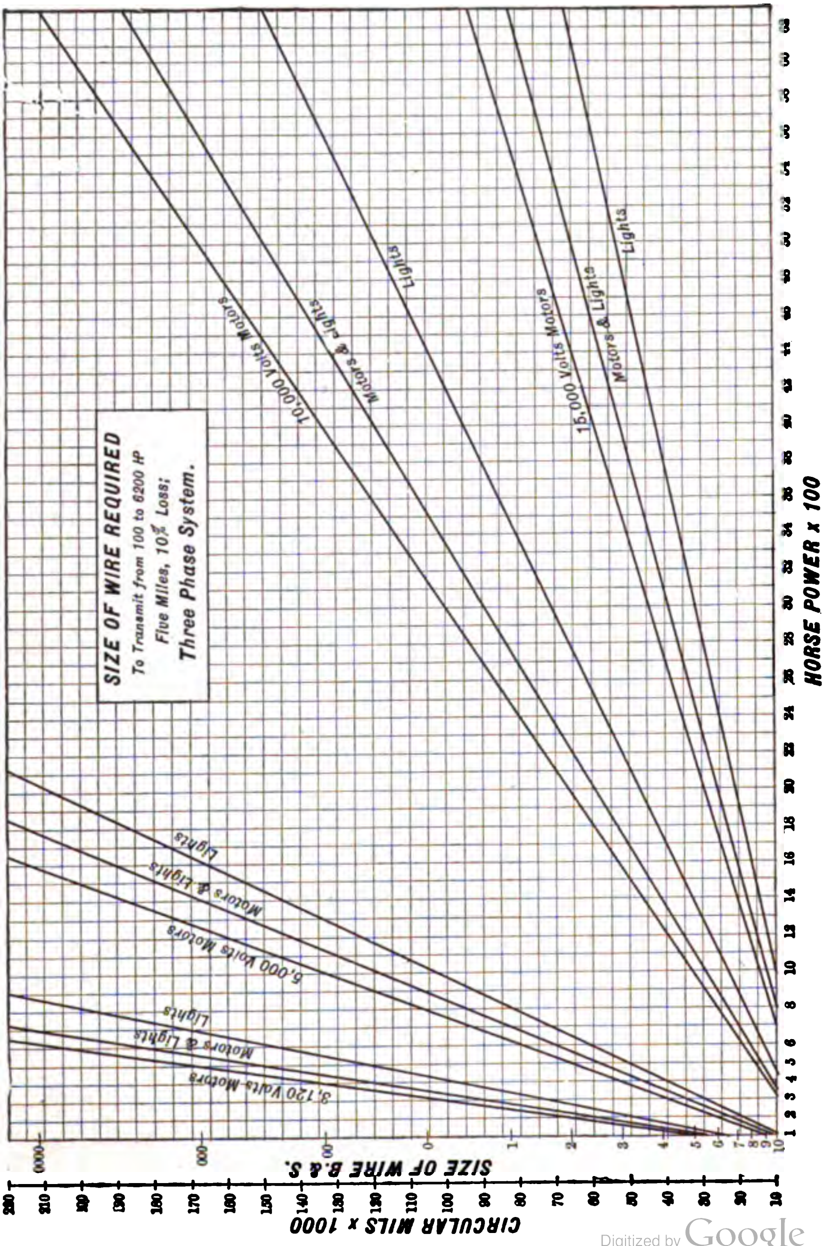

SIZE OF WIRE REQUIRED
To Transmit from 100 to 6200 HP
Five Miles, 10% Loss;
Three Phase System.
10,000 Volts Motors
Motors & Lights
Lights
15,000 Volts Motors
Motors & Lights
Lights
5,000 Volts Motors
Motors & Lights
Lights
3,120 Volts Motors
Motors & Lights
Lights
HORSE POWER x 100
SIZE OF WIRE B. & S.
CIRCULAR MILS x 1000

Fig. 205.

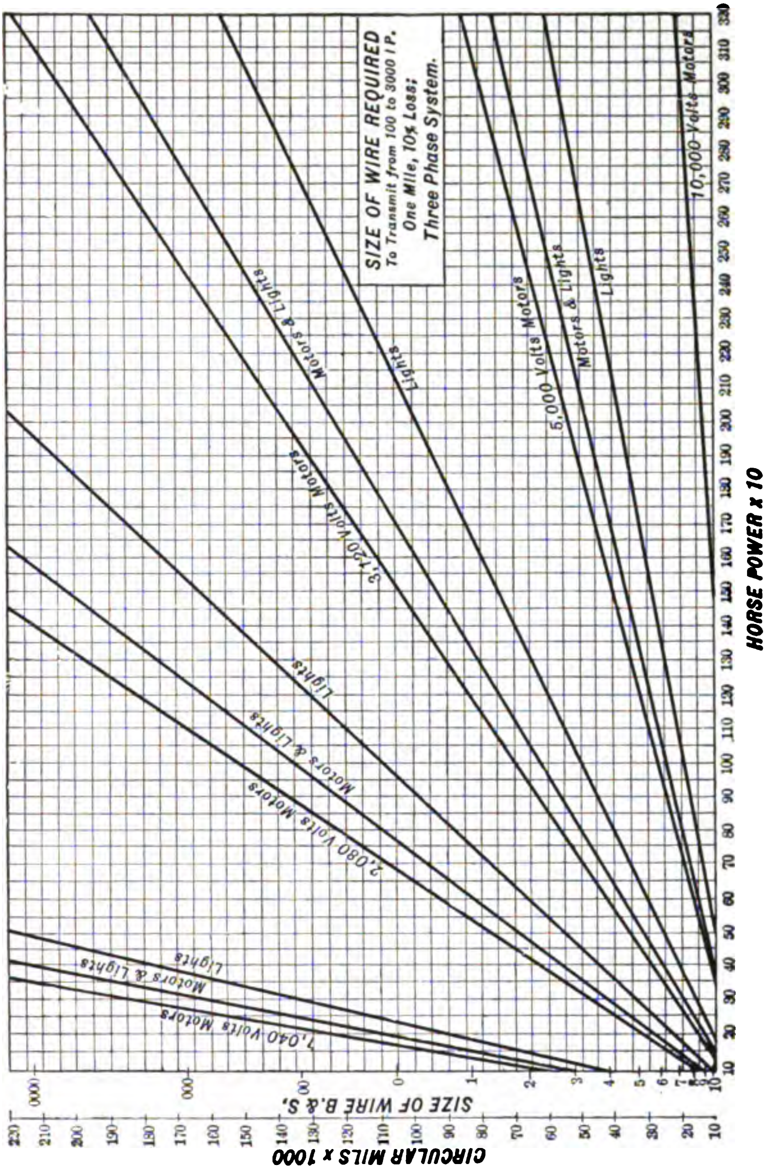

SIZE OF WIRE REQUIRED
To Transmit from 100 to 3000 H.P.
One Mile, 10% Loss;
Three Phase System.
10,000 Volts Motors
Lights
Motors & Lights
5,000 Volts Motors
Lights
Motors & Lights
3,120 Volts Motors
Lights
Motors & Lights
2,080 Volts Motors
Lights
Motors & Lights
1,040 Volts Motors
HORSE POWER x 10
SIZE OF WIRE B.& S.
CIRCULAR MILS x 1000

Fig. 206

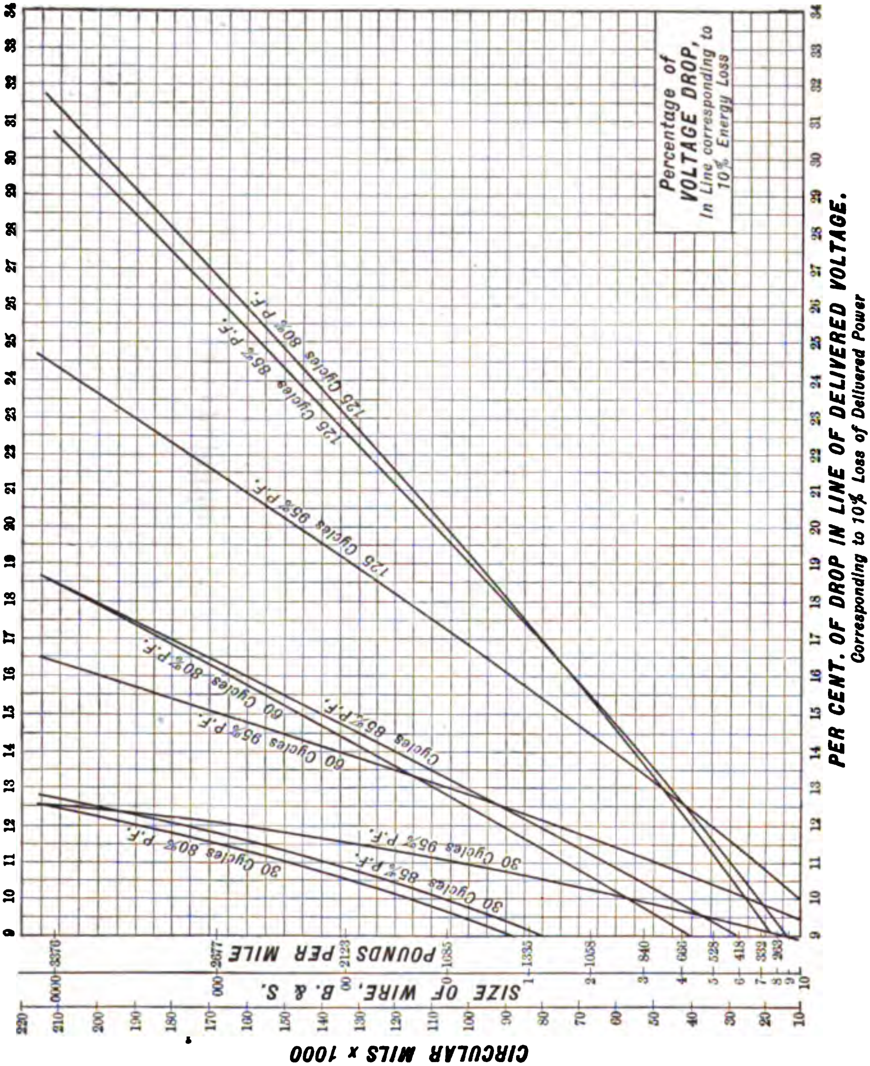

Percentage of VOLTAGE DROP, In Line corresponding to 10% Energy Loss
PER CENT. OF DROP IN LINE OF DELIVERED VOLTAGE.
Corresponding to 10% Loss of Delivered Power
125 Cycles 80% P.F.
125 Cycles 85% P.F.
125 Cycles 95% P.F.
60 Cycles 80% P.F.
Cycles 85% P.F.
60 Cycles 95% P.F.
30 Cycles 95% P.F.
30 Cycles 85% P.F.
30 Cycles 80% P.F.
POUNDS PER MILE
SIZE OF WIRE, B. & S.
CIRCULAR MILS x 1000

Fig. 207.

The section of the neutral conductor should be about $\frac{131 \times 2 \times 105{,}592}{322} = 86{,}000$ *C.M.* We may use one No. 1 B. & S. wire with a section of 83,694 *C.M.* for the neutral.

Graphical Illustration. — The curves on pages 354–356, Figs. 205, 206, and 207, have been calculated from the preceding formula and table of constants relating to the three-phase system only. They will be found useful for calculating and approximately determining the copper required for transmitting any amount of power any distance at voltages varying from 1,000 to 15,000.

For cases that fall outside the limits of the curves, the size of the wire may be found by applying the following rules:

With given power delivered, line loss, and voltage, the cross section of the conductor will vary directly as the distance.

With given distance of transmission, line loss, and voltage, the cross section of the conductor will vary directly as the power delivered.

With given distance of transmission, power delivered, and voltage, the cross section of the conductor will vary inversely as the loss of energy in the line.

With given distance, power delivered, and line loss, the cross section of the conductor will vary inversely as the square of the voltage.

The voltages are taken as those at the receiving end. The line loss has been assumed to be 10 per cent of the delivered energy. In plotting the curves the following power factors have been assumed:

For lighting load	95%
For mixed load of induction motors and lights . .	85%
For induction motor load	80%

To illustrate the use of the curves, find the size of the wire required to transmit 5,100 H.P., to be used for incandescent lighting, a distance of five miles, the current loss being 10 per cent, and the pressure at the primaries of step-down transformers, 10,000 volts. The curve (Fig. 167) shows that each of the three wires must have a cross section of 120,000 circular mils. If the power delivered is to be consumed by induction motors, other conditions remaining the same, the conductor must have a cross section equivalent to 170,000 circular mils each, or slightly larger than No. 000 wire. Or, supposing the wire to have been strung on the assumption that lights would be supplied, the line loss and pressure being the same as above, it will be seen that, if the load is changed to induction motors, only 3,600 H.P. will be delivered from these lines. This is a striking illustration of the decrease in the carrying capacity of the line, due to low power factors, which load the line, and the generators as well, with so-called wattless current.

If the distance is raised to ten miles, the size of wire required for the same transmission is doubled in both the above examples. If the distance is increased to ten miles, and the energy loss reduced to five per cent, the cross section of conductor will have to be made four times as great.

Three wires of about No. 3 size will transmit a lighting load of 5,100 H.P. a distance of five miles, the pressure being 15,000 at the receiving end. It will take three conductors of cross section corresponding to a size between No. 1 and No. 2 to transmit the same power for induction motor use, and three No. 2 wires to transmit the same energy for a mixed load of lights and motors.

For determining the size of transmission lines with vol-

tages of 5,000 and less, the curves in Fig. 206 will be found most convenient.

Fig. 207 represents the curves of percentage drop of voltage in transmission lines, at varying frequencies and power factors. The curves show the values of the constant, M, plotted from the table on page 349, and are based on 10 per cent energy loss in line.

A study of the curves shows some interesting facts. When the transmission is effected at 30 cycles, it will be noticed that, for all commercial sizes of wires, the voltage drop is less with a load of low power factor than with one of high power factor. For illustration, assume that the transmission requires conductors of 120,000 circular mils each, the energy loss being 10 per cent of the delivered power. At 30 cycles, the drop in voltage is 10.1 per cent when the power factor is 80 per cent, 10.4 per cent when the power factor is 85 per cent, and 11.3 per cent when the power factor is 95 per cent. On the other hand, the same transmission at 125 cycles shows a higher voltage drop with low power factors. The voltage drops 18.3 per cent with a 95 per cent power factor, 21.2 per cent with an 85 per cent power factor, and 21.7 per cent when the power factor is 80 per cent.

A curious condition exists at 60 cycles. The voltage drop is less with a power factor of 95 per cent, than when the power factor is 85 per cent; but an 80 per cent power factor gives a drop approximately the same as that due to a power factor of 95 per cent. The curves also graphically illustrate the reduction in voltage drop to be gained by subdividing the conductors. A No. 00 wire, used in a 60 cycle transmission of power for induction motors, shows a drop of 14.3 per cent. By subdividing the wire into two No. 2 wires, and equivalent cross section, the voltage drop is reduced to 10.6 per cent.

It will be seen, from the curves, that, by subdividing the conductor sufficiently, a wire of a size can be selected, which, for all commercial power factors and frequencies, will transmit any amount of power, with a drop of voltage in the line actually less than the energy loss. This apparent anomaly is explained in Chapter I., under the paragraph, "Voltage Drop Dependent on Load Characteristic."

Resonance Effect. — What is known as the resonance effect of a circuit is the rise of *E.M.F.* at the far end, above that at the generator end. This phenomenon takes place when the natural period of discharge of a circuit is equal to the frequency of the generator *E.M.F.* It is complete when the self-induction and capacity exactly neutralize each other. The charging current of the line, due to the capacity, then produces an *E.M.F.* of self-induction equal to the generator *E.M.F.*

In transmission lines, where the inductance and capacity do not exactly neutralize each other, it is possible for partial resonance to be present. The circuit can be brought into complete resonance by the addition of a condenser or a reactance, according as it lacks the proper amount of either capacity or inductance. It is conceivable that an unexpected rise of pressure may occur of sufficient extent to destroy the insulation of line and of apparatus.

The rise of pressure due to complete resonance is limited by the ohmic resistance of the circuit. For this reason, and because practical transmissions of power are accomplished at a comparatively low frequency, the possible rise of pressure at the receiving end is not likely to be dangerously high.

For very long power transmissions, where resonance effects may be expected, it is desirable to employ generators producing an *E.M.F.* wave which is sinusoidal. A

distorted wave of *E.M.F.* of the same period can be resolved into a number of simple harmonic components of a higher frequency. These higher harmonics have the same effect as an *E.M.F.* wave of the same frequency and magnitude.

Another form of resonance effect is that which occurs during both the making and the disruption of a current of high tension, especially in long distance transmission lines. It is found that the oscillatory discharge in the arc under these conditions may become of such magnitude as to seriously endanger the insulation of the line and of apparatus connected thereto. As has been described in the section under high tension switches, this effect is particularly noticeable in those interruptions to the current which are effected in the open air.

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